

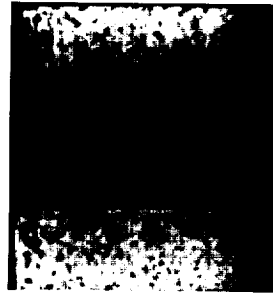
NASA's Microgravity Science Research Program

1996

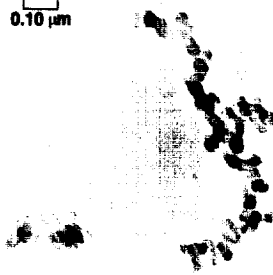
Annual Report

*In the microgravity
environment of space, the
masking forces of Earth's gravity
are stripped away, allowing
scientists to pursue research not
possible in ground-based
laboratories.*

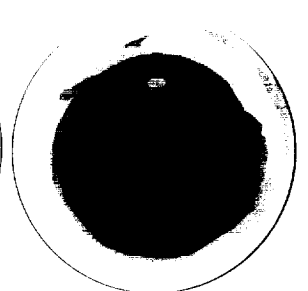
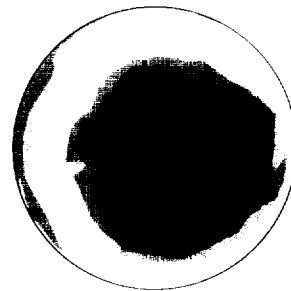
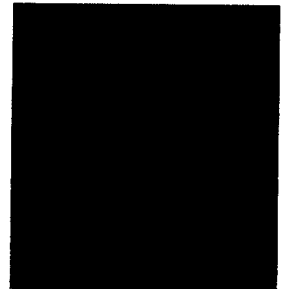
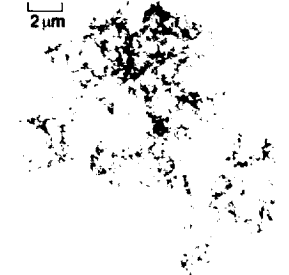
TM-108536



0.10 μm



2 μm



NASA's Microgravity Science Research Program

1996

Annual Report

NASA TM-108536



National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

On the Cover

Descriptions of the cover photographs are given below. Earth-based samples are shown on the left; by comparison, samples produced in microgravity are shown on the right.

Biotechnology: Tissues grown in NASA's bioreactor system provide scientists with invaluable information about treatments for human diseases.

1. Colon cancer manifests as polyps in the colon. Standard culture techniques do not provide three-dimensional models.
2. The space-based bioreactor grows three-dimensional tumors with 10 times more clarity than cultures grown on Earth.

Combustion Science: Soot from combustion is critical to many manufacturing and power generation industries. The practical implications of this research range from energy conservation, to pollution control and fire safety.

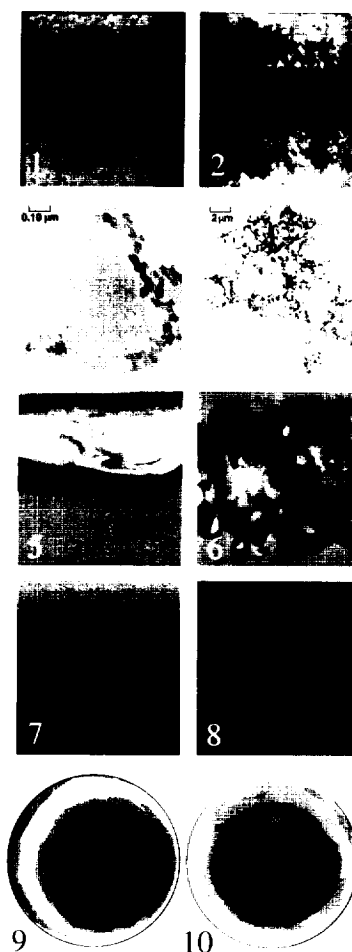
3. Scientists now know that gravity affects soot particle size and aggregation, and that microgravity offers a unique way to study combustion products. The soot particle formed in normal gravity is linear and is 0.5-micron long.
4. The soot particle formed in microgravity is much larger, with a length of 18 micrometers and a different geometrical shape.

Fluids Physics: To enable advances in materials processed on Earth, scientists need a better understanding of fluid processes that play a role in the production of most materials, including new high-strength alloys and temperature-resistant glasses and ceramics for building everything from better electric power plants to future spacecraft.

5. Two-phase flow is important in a variety of industrial, as well as space processes. This two-phase liquid flow in a horizontal pipe tends to separate into layers, with gas flowing into the upper part of the pipe.
6. In microgravity, the flow becomes more symmetrical and has a different structure.

Fundamental Physics: NASA research lays a foundation for new discoveries by allowing scientists to study with unprecedented precision the most fundamental physics laws that govern the behavior of matter.

7. In a fluid near its phase transition, Earth's gravity makes the fluid nonuniform, causing the bottom of the sample to have a density greater than the top, so the region very near to the transition is occupied by only a small portion of the fluid.
8. In microgravity, the fluid is uniform, and the whole sample approaches the phase transition under the science team's control.



Materials Science: This discipline studies how materials form and how the forming process controls various properties. For example, the speed and amount of information that can be stored and sent by computers may be increased by better control of how the semiconductor's structure forms.

9. A semiconductor's usefulness is determined by how atoms are ordered within the crystal's underlying three-dimensional structure. While this mercury telluride and cadmium telluride alloy sample mixes completely in Earth-based laboratories, convective flows prevent them from mixing uniformly. Compositional variation is denoted by the grey scale.
10. In space, the ingredients mix more homogeneously, resulting in a superior product.

Executive Summary

The ongoing challenge faced by NASA's Microgravity Science Research Program is to work with the scientific and engineering communities to secure the maximum return from our Nation's investments by: (1) assuring that the best possible science emerges from the science community for microgravity investigations, (2) ensuring the maximum scientific return from each investigation in the most timely and cost-effective manner, and (3) enhancing the distribution of data and applications of results acquired through completed investigations to maximize their benefits.

NASA Continued to Build a Solid Research Community of Microgravity Researchers for the Forthcoming *International Space Station* Era

During FY 1996, the NASA Microgravity Science Research Program continued investigations selected from the 1994 combustion science, fluid physics (which included fundamental physics), and materials science NASA Research Announcements (NRA's). The third biennial NRA in the area of microgravity biotechnology was released that year, with more than 130 proposals received in response. Selection of research for funding is expected in early

1997. The principal investigators (PI's) chosen from these NRA's will form the core of the program at the beginning of the *International Space Station (ISS)* era.

The number of PI's in FY 1996 increased almost 20 percent over FY 1995, the number of journal articles increased 12 percent, and the number of technical presentations increased almost 30 percent. The total number of tasks funded grew from 347 in FY 1995 to 508 in FY 1996.

The National Research Council's (NRC) Committee on Microgravity Research (CMGR) began work to identify the most appropriate role for the microgravity science community to play in support of NASA's Human Exploration and Development of Space (HEDS) Enterprise. In

FY 1996, the NRC CMGR also published an assessment of the NASA microgravity flight data archiving activities, affirming the use of the Experiment Data Management Plan (EDMP) as the appropriate mechanism for an archival system.

Continuing Strides Were Made in International and Inter-Governmental Cooperation

Data from microgravity research equipment placed on the Russian space station *Mir* continue to be analyzed by NASA microgravity scientists and engineers. Planning for *ISS* facilities continued with respect to the Biotechnology Facility (BTF), the Space Station Furnace Facility (SSFF),

the Fluids and Combustion Facility (FCF), and a newly planned Low-Temperature Microgravity Physics (LTMP) facility.

Letters of agreement with Japan and Canada have improved the research facilities available to U.S. ground-based microgravity PI's. Japan made their highly sophisticated 10-second drop tower facilities available to a broad range of U.S. combustion scientists. The Canadian Space Agency (CSA) has developed and offered to the United States a large motion isolation mount that can be used in U.S. parabolic aircraft to provide an improved lower gravity environment on the aircraft, an integral part of the ground-based research program.

Cooperation with the National Institutes of Health (NIH) continued to address the technical challenges of three-dimensional tissue growth, crystallization of high quality protein crystals, and the early detection of cataracts by supporting multidisciplinary research teams. These research teams allow some of the best American scientists and bioengineers to address these complex problems and accelerate technology development. Through NASA-NIH cooperation, NASA has funded 28 research proposals and has also supported NIH-approved researchers to test tissue samples in NASA bioreactors at NASA's Johnson Space Center (JSC).

The Third United States Microgravity Payload and the Life and Microgravity Spacelab Missions, and Other Space Shuttle Missions, Yielded Significant Results for Microgravity Investigations

The Third United States Microgravity Payload (USMP-3) and the Life and Microgravity Spacelab (LMS) missions yielded a wealth of microgravity data in FY 1996. The USMP-3 mission included a fluids facility and three solidification apparatus, each designed to examine a different type of crystal growth. The fundamental physics Critical Fluid Light Scattering Experiment/Zeno successfully completed its second flight on USMP-3. Also on USMP-3, the Isothermal Dendritic Growth Experiment (IDGE) became the first U.S. microgravity experiment to be commanded and controlled from the PI's home institution, in this case, a university. LMS research in biotechnology, fluid physics, and materials science allowed U.S. investigators to use instruments developed by the European Space Agency (ESA), thus broadening the basis for international cooperation in space research. The LMS mission was the first to fly the ESA Advanced Gradient Heating Furnace (AGHF).

During FY 1996, the biotechnology program supported 20 experimental instrument flights in protein crystal growth (PCG) and cell science, with more than 1,500 protein samples flown. The first long-duration flight of a cell and tissue culturing device was placed in orbit on the *Mir* during FY 1996.

Microgravity Science Research Program Expands Education and Outreach Activities

Microgravity News, which provides quarterly updates on NASA's Microgravity Science Research Program, has been reaching increasing numbers of people in the past year. The total distribution of each issue of the newsletter reached 9,000 for CY 1996, up from 2,500 in 1995. Progress continued in FY 1996 on the Microgravity Science Research Program World Wide Web (WWW) sites, beginning an effort to integrate numerous microgravity Web pages.

Through NASA's Graduate Student Research Program (GSRP), 43 graduate students were funded to perform ground-based microgravity research in FY 1996. That year, more than 6,000 microgravity science educational posters, teachers guides, and supplementary curricular materials were distributed at various conferences. Over 1,200 teachers requested that they be added to the microgravity education and outreach mailing list. This brought the total number of kindergarten through grade 12 (K-12) teachers on the mailing list to 1,865 (including 445 kindergarten and elementary, 522 middle school, and 898 high school educators).

Table of Contents

1. Introduction	1
2. Program Goals for FY 1996	3
3. Program Approach for FY 1996	4
<i>Program Overview</i>	4
<i>National Institutes of Health Cooperation</i>	4
<i>International Cooperation</i>	5
<i>Advisory Groups</i>	7
4. Microgravity Research Conducted in FY 1996	8
<i>Biotechnology</i>	8
<i>Combustion Science</i>	13
<i>Fluid Physics</i>	18
<i>Fundamental Physics</i>	25
<i>Materials Science</i>	30
5. Technology, Hardware, and Education Outreach	38
<i>Advanced Technology Development 1996</i>	38
<i>Hardware</i>	42
<i>Education and Outreach Activities</i>	46
6. Program Resources for FY 1996	48
7. For More Information	50
<i>Microgravity Research Division homepage:</i> <i>http://microgravity.msad.hq.nasa.gov/</i>	

Abbreviations and Acronyms

AADSF	Advanced Automated Directional Solidification Furnace	ESA	European Space Agency
ACCG	American Conference on Crystal Growth	EXPRESS	Expedite Payload Resources to Space Station
AGHF	Advanced Gradient Heating Facility	FCF	Fluids and Combustion Facility
AIAA	American Institute of Aeronautics and Astronautics	FDA	Food and Drug Administration
AIChE	American Institute of Chemical Engineers	FFFT	Forced Flow Flamespread Test
ANL	Argonne National Laboratory	FGB	Functional Cargo Block
APCF	Advanced Protein Crystallization Facility	GAS	Get Away Special
ASI	Agenzia Spaziale Italiana (Italian Space Agency)	GSFC	Goddard Space Flight Center
ASME	American Society of Mechanical Engineers	GSRP	Graduate Student Research Program
ATD	Advanced Technology Development	HEDS	Human Exploration and Development of Space
BCAT	Binary Colloidal Alloy Test	IDGE	Isothermal Dendritic Growth Experiment
BTF	Biotechnology Facility	ISS	<i>International Space Station</i>
BTS	Biotechnology System	JPL	Jet Propulsion Laboratory
CGH	Coupled Growth in Hypermonotectics	JSC	Johnson Space Center
CHeX	Confined Helium Experiment	LaRC	Langley Research Center
CMGR	Committee on Microgravity Research	LeRC	Lewis Research Center
CNES	French National Center for Space Studies	LMD	Liquid Metal Diffusion
CSA	Canadian Space Agency	LMS	Life and Microgravity Spacelab
DARA	Deutsche Agentur für Raumfahrt Angelegenheiten (German Agency for Space Affairs)	LMSAAC	Life and Microgravity Sciences and Applications Advisory Committee
DARTFire	Diffusive and Radiative Transport in Fires	LTMP	Low Temperature Microgravity Physics
DYNAMX	Critical Dynamics in Microgravity Experiment	MEPHISTO	Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit
EDMP	Experiment Data Management Plan	MGBX	Microgravity Glovebox
		MICREX	Microgravity Research Experiments

MIM	Microgravity Isolation Mount	SDLE	Self-Diffusion in Liquid Elements
MISTE	Microgravity Investigation of Scaling Theory Experiment	SIV	stereo imaging velocity
MIT	Massachusetts Institute of Technology	SOFBALL	Structure of Flame Balls at Low Lewis Number
MSAD	Microgravity Science and Applications Division	SPARTAN	Shuttle Pointed Autonomous Research Tool for Astronomy
MSDA	Microgravity Science Data Archive	SPIE	Society of Photo-Optical Instrumentation Engineers
MSFC	Marshall Space Flight Center	SQUID	Superconducting Quantum Interference Device
MSL	Microgravity Science Laboratory	SSFF	Space Station Furnace Facility
NASDA	National Space Development Agency of Japan	STEP	Satellite Test of the Equivalence Principle
NEDO	New Energy and Industrial Technology Development Organization (Japan)	STS	Space Transportation System
NIH	National Institutes of Health	SUE	Superfluid Universality Experiment
NMRP	NASA/Mir Research Program	TEM	Technology Evaluation of the MIM
NRA	NASA Research Announcement	TSSA	Two-Stage Series Array SQUID amplifier
NRL	Naval Research Laboratory	UCLA	University of California, Los Angeles
OLMSA	Office of Life and Microgravity Sciences and Applications	UCR	University of California, Riverside
PCAM	Protein Crystallization Apparatus for Microgravity	USC	University of Southern California
PCG	protein crystal growth	USML	United States Microgravity Laboratory
PEP	Particle Engulfment and Pushing	USMP	United States Microgravity Payload
PI	principal investigator	VCU	Virginia Commonwealth University
PMZF	Programmable Multizone Furnace	WWW	World Wide Web
RSA	Russian Space Agency		
SAL	Spread Across Liquids		
SAMS	Space Acceleration Measurement System		

Introduction

This FY 1996 annual report describes key elements of the NASA Microgravity Science Research Program as conducted by the Microgravity Science and Applications Division (MSAD) within NASA's Office of Life and Microgravity Sciences and Applications (OLMSA). The Program's goals, approach taken to achieve those goals, and resources that were available are summarized. A "snapshot" of the Program's status at the end of FY 1996 and a review of highlights and progress in the ground- and flight-based research during that year are provided. Also described are major space missions that flew during FY 1996, plans for utilization of the research potential of the Russian *Mir* space station and the *International Space Station (ISS)*, the Advanced Technology Development (ATD) Program, and various educational/outreach activities. This NASA-funded program supports investigators from university, industry, and Government research communities needing a space environment to study phenomena directly or indirectly affected by gravity.

The Microgravity Science Research Program is a natural extension of traditional Earth-based laboratory science, in which experiments performed benefit from the stable, long-duration microgravity environment available in orbiting spacecraft. The microgravity environment affords substantially reduced buoyancy forces, hydrostatic pressures, and sedimentation rates, allowing gravity-related phenomena and phenomena masked by Earth's gravity to be isolated and controlled, permitting measurements to be made with an accuracy that cannot be obtained in ground-based laboratories.

The Microgravity Science Research Program supports both basic and applied research in five key areas:

- Biotechnology—focusing on macromolecular crystal growth as well as the use of the unique space environment to assemble and grow mammalian tissue.
- Combustion science—focusing on the processes of ignition, propagation, and extinction during combustion of gaseous, liquid, and solid fuels, and on combustion synthesis in a low-gravity environment.
- Fluid physics—including aspects of fluid dynamics and transport phenomena affected by the presence of gravity.
- Fundamental physics—including the study of critical phenomena; low-temperature, atomic, and gravitational physics; and other areas of fundamental physics where significant advantages exist for studies in a low-gravity environment.
- Materials science—including electronic and photonic materials, glasses and ceramics, polymers, and metals and alloys.

Experiments in these areas are typically directed at providing a better understanding of gravity-dependent physical phenomena and exploring phenomena obscured by the effects of gravity. Scientific results are used to challenge or validate contemporary scientific theories, identify and describe new experimental techniques that are unique to the low-gravity environment, and engender the

development of new theories explaining unexpected results. These results and the improved understanding accompanying them can lead to: improving combustion efficiency and fire safety; reducing combustion-generated pollutants; developing new technologies in industries as varied as medicine, chemical processing, and materials processing; developing or improving pharmaceuticals; and expanding fundamental knowledge in a broad range of science disciplines destined to become the foundation for scientific and technological discoveries in the future.

A complementary document to this Microgravity Science Research Program annual report is the *Microgravity Science and Applications Program Tasks and Bibliography for FY 1996*, NASA Technical Memorandum 4780, March 1997. Detailed information on the research tasks funded by the Microgravity Science Research Program during FY 1996 is listed in that report, which serves as an excellent reference for supplementary information to this annual report. Also of interest is the *NASA Microgravity Science and Applications Program Strategic Plan*, issued in June 1993, a guide for development and implementation of the Microgravity Science Research Program plans and activities to the year 2000. The *Marshall Space Flight Center (MSFC) Strategic Implementation Plan*, January 1996, describes MSFC's Lead Center role for the Microgravity Science Research Program. Another complementary document is NASA's *Microgravity Technology Report*, first published in December 1995, summarizing advanced technology development and technology transfer

activities through FY 1994. The second *Technology Report*, covering FY 1995 activities, was published in 1996. A third edition, covering FY 1996 activities, will be published in the spring of 1997.

Table 1 summarizes information from the *Microgravity Science and Applications Program Tasks and Bibliography for FY 1996*, which may be of particular interest to the reader.

Data for FY 1993, FY 1994, and FY 1995 are shown for comparison with FY 1996 statistics.

TABLE 1.—FY 1993 through FY 1996 research task summary: overview information and statistics.

	FY 1993	FY 1994	FY 1995	FY 1996
Total Number of Principal Investigators	196	243	290	358*
Total Number of Co-Investigators	268	252	287	396
Total Number of Research Tasks	243	316	347	508
Total Number of Bibliographic Listings	767	944	1,200	1,573
• Proceeding Papers	110	145	140	237
• Journal Articles	446	371	526	600
• NASA Technical Briefs	6	13	11	14
• Science/Technical Presentations	201	391	509	706
• Books/Chapters	5	24	14	16
Total Number of Patents Applied for or Awarded	7	1	1	2
Number of Graduate Students Funded	329	434	534	780
Number of Graduate Degrees Based on MSAD-Funded Research	61	125	178	247
Number of States With Funded Research (Including District of Columbia)	32	36	34	35
FY Microgravity Science (\$ in Millions) and Applications Budget	179.3	188.0	163.5	159.0

*Number includes no-cost extensions.

Microgravity Science and Applications Research Tasks and Types — Responsibilities by Center —

Types of Research (by Fiscal Year)

<i>Center</i>	<i>Ground</i>				<i>Flight</i>				<i>ATD</i>				<i>Center Totals</i>			
	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996
Jet Propulsion Laboratory	29	27	28	45	7	7	5	7	3	3	3	3	39	39	36	55
Johnson Space Center	11	10	34	32	1	0	1	1	0	0	0	1	12	10	35	34
Langley Research Center	5	3	3	2	2	2	2	1	1	0	0	0	8	5	5	3
Lewis Research Center	87	131	125	203	29	35	32	46	5	5	6	6	121	170	163	255
Marshall Space Flight Center	36	62	76	124	25	25	25	32	2	4	6	4	63	91	107	160
Goddard Space Flight Center	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1
Research Task Totals	168	233	266	406	64	69	65	87	11	13	16	15	243	316	347	508

Program Goals for FY 1996

To use the microgravity environment of space as a tool to advance knowledge; to use space as a laboratory to explore the nature of physical phenomena, contributing to progress in science and technology on Earth; and to study the role of gravity in technological processes, building a scientific foundation for understanding the consequences of gravitational environments beyond Earth's boundaries.

From the Microgravity Science Research Program's
FY 1996 Mission Statement

During FY 1996, the NASA Microgravity Science Research Program's plans for establishing a Lead Center for Microgravity Research progressed to the implementation stage. The plan to implement the Lead Center at MSFC was signed by Dr. Arnauld Nicogossian, Associate Administrator for Life and Microgravity Sciences and Applications at NASA Headquarters (HQ), and by Mr. Wilbur Trafton, NASA HQ Associate Administrator for Space Flight. The Microgravity Science Research Program goals for FY 1996 were:

Goal 1—Sustain a leading edge research program focused in the areas of biotechnology, combustion science, fluid physics, fundamental physics, and materials science that effectively engages the National research community.

Goal 2—Foster an interdisciplinary community to promote synergy, creativity, and value in carrying out the research program.

Goal 3—Enable research through development of appropriate infrastructure of ground-based facilities, diagnostic capabilities, and flight facilities/opportunities,

including international cooperative efforts, to meet science requirements.

Goal 4—Promote the exchange of scientific knowledge and technological advances among academic, governmental, and industrial communities. Disseminate results to the general public and to educational institutions.

Goal 5—Raise the awareness of the microgravity research community regarding the long-term direction of the Human Exploration and Development of Space strategic enterprise, and discuss with the community the role of the microgravity research in support of Agency objectives.

Program Approach for FY 1996

Program Overview

The Microgravity Science Research Program conducts research in space using an established process to select scientific investigations via the periodic release of NASA Research Announcements (NRA), with external peer review of proposals received in response to these announcements. All new investigations are selected by the external peer review process for either ground-based or flight-definition studies. In the latter case, there is an initial ground-based definition phase to establish the concept, verify the need for flight experiments, and define the scope of these experiments; further peer review is then utilized to determine which of the flight-definition experiments will actually be approved to progress to using space facilities. With this overall approach, research within the Microgravity Science Research Program extends from analytical studies and relatively low-resource ground-based experimental studies to substantial space-flight experiments.

In 1996, NASA continued investigations selected from the 1994 combustion science, fluid physics (including fundamental physics), and materials science NRAs. The investigations currently supported will define the first phase of *International Space Station (ISS)* microgravity research. NASA received 550 proposals in response to the 1994 NRAs in the areas of fluid physics, low-temperature/laser cooling physics, and materials science. Of those proposals, 168 scientists have been selected to receive grants worth a total of approximately \$17 million for conducting ground- and space-based research. The breakdown of recipients by area is as follows: fluid physics, 84; low-temperature/laser cooling physics, 25; and materials

science, 63. Also recently announced was the selection of researchers for the 1995 NRA in combustion science. Out of 110 proposals, NASA chose to fund 20 researchers with grants totaling more than \$7 million.

The third biennial NRA in the area of microgravity biotechnology was released in 1996. More than 130 proposals were received in response to the announcement. Selection of research for funding is expected in early 1997.

The Microgravity Science Research Program supports a relatively large number of analytical and experimental studies utilizing ground-based facilities, development of high-quality flight investigations, and further development of ground-based facilities and advanced diagnostics for both ground-based and flight experiments. In the ground-based facilities, low-gravity test environments of varying duration are available—up to 5 seconds of high-quality microgravity time in drop tubes/towers, 20 seconds of considerably lower-quality microgravity time in parabolic aircraft, and up to 12 minutes of high-quality microgravity time in suborbital rockets. To support the space-based investigations, the flight program selects the most cost-effective option from a broad range of hardware and carrier resources.

To ensure the best use of resources and scientific talent to achieve program goals, the Microgravity Science Research Program observes the following rules to guide the decision making process:

- Maintain and, when successive peer-evaluation warrants, complete the ongoing program.

- Identify and nurture emerging experimental concepts and areas of investigation with substantial scientific potential.
- Identify and sustain a broad capability for experimentation in space, utilizing all available carriers.
- Identify and pursue initiatives to support effective changes and growth within the Microgravity Science Research Program.

These decision rules are discussed in more detail in the NASA *Microgravity Science and Applications Program Strategic Plan* published in 1993.

National Institutes of Health Cooperation

The FY 1996 NASA appropriations included augmentations for collaborative NASA–National Institutes of Health (NIH) biotechnology programs. In using these funds, the NASA areas of emphasis are:

- Continuation of joint NASA–NIH centers to accelerate the transfer of NASA technology and allow its application to biomedical research.
- Development of advanced tissue culturing technology and application of this breakthrough technology to biomedical research and developmental biology.
- Development of advanced protein crystal diagnostic technologies to advance structural biology and drug design to fight a number of diseases.

The NASA–NIH collaboration offers an opportunity to address the technical challenges of three-dimensional tissue growth, crystallization of high-quality protein crystals, and the early detection of cataracts by supporting multidisciplinary research teams. These research teams allow some of the best American scientists and bioengineers to address these complex problems and accelerate development of the technologies.

To speed up the pace of technology transfer in the biotechnology areas begun under the NASA–NIH interagency agreement, two multidisciplinary research centers are currently supported—the Massachusetts Institute of Technology (MIT) in Cambridge, MA, and the Wistar Institute in Philadelphia, PA. Through NASA–NIH cooperation, NASA has funded 28 research proposals and has also supported NIH-approved researchers to test tissue samples in NASA bioreactors at NASA's JSC. This has proven to be a very important undertaking in stimulating researchers to test NASA technology and gaining acceptance in the larger biomedical community.

A cooperative effort continued with the National Institute of Child Health and Human Development to transfer NASA's bioreactor technology for use in AIDS research, with researchers using human tonsil, lung, adenoid, and lymph node cultures to assess infectivity of the HIV virus on these tissues.

The Microgravity Science Research Program also has begun collaborative work with the NIH Laboratory for Structural Biology to develop the next generation of x-ray

diagnostic tools for laboratory use. Using new technology, early development has shown this x-ray system to produce a much brighter beam, with a significant reduction in power use. This cooperative arrangement includes developing standard manufacturing processes and infusing this new technology into laboratories across the country.

International Cooperation

Letters of agreement with Japan and Canada have improved the research facilities available to U.S. ground-based microgravity principal investigators (PI). Collaborative research between Japan and the United States was established and successfully conducted in the Japanese 10-second drop tower and NASA Lewis Research Center's (LeRC) 2.2-second and 5-second drop towers for investigations of fuel droplets and solid fuel burning. This collaborative research saved substantial resources for each country by avoiding duplicative construction of hardware, while gaining new scientific knowledge. The Canadian Space Agency (CSA) has developed and offered to the United States a large motion isolation mount that can be used in U.S. parabolic aircraft to provide an improved lower gravity environment on the aircraft, an integral part of the ground-based research program.

The European Space Agency (ESA) developed the Spacelab module used in the United States Microgravity Laboratory (USML), the Life and Microgravity Spacelab

(LMS), and the Microgravity Science Laboratory (MSL) missions. The Spacelab glovebox that flew on USML–2 in November 1995 was developed by ESA.

In exchange for U.S. use of this glovebox during that mission, NASA has twice flown two units of the ESA Advanced Protein Crystallization Facility (APCF) in the space shuttle middeck. Both U.S. and European investigators used the APCF on this quid-pro-quo agreement with ESA. Each flight involved two APCF units, with a total of 96 protein crystal growth (PCG) cells, 48 of which were contributed by U.S. investigators.

Research aboard the LMS mission in biotechnology, fluid physics and transport phenomena, and materials science allowed U.S. investigators to use instruments developed by ESA, thus broadening the basis for international cooperation in microgravity research. Both U.S. and international PIs used the European-developed Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (MEPHISTO) furnace and the AGHE, and the U.S.-developed Isothermal Dendritic Growth Experiment (IDGE) to conduct numerous materials science experiments.

Mir: The Russian Space Station

The Microgravity NASA/*Mir* Research Program (NMRP) seeks to mitigate risk in scientific, technological, logistical, and operational planning for use of the *ISS*. Additional goals of the NMRP are to characterize the microgravity environment

on the *Mir* and to conduct specific U.S. investigations in microgravity science and applications research disciplines. The NMRP has utilized modified space shuttle experiment apparatus, flight samples, science operations, and data analysis/procedures in order to allow U.S. investigators to fully maximize the capabilities of the *Mir* space station.

Mir research and support provides for early science opportunities during *ISS* Phase 1 by conducting long-duration science aboard the *Mir*, as well as shorter duration science investigations on the space shuttle rendezvous missions to *Mir*. The primary objectives of these flights are to rendezvous and dock with the *Mir*; perform on-orbit, joint U.S./Russian science and research; perform on-orbit joint operations to serve as a platform for future *ISS* operations; resupply *Mir* logistics; and exchange the American astronauts on board the *Mir*. Four space shuttle missions to *Mir* were completed by the end of FY 1996.

During FY 1996, the Microgravity Science Research Program significantly increased its participation in scientific experiments conducted on the *Mir*. Three investigative facilities were located on board the *Mir* and 15 long-duration investigations performed. An international cooperative effort was used to transport payloads to the *Mir*, using both U.S. Space Transportation System (STS) and Russian launch vehicles.

In November 1995, the STS-74 mission delivered a new Russian-built docking module to the *Mir* to allow the space shuttle to dock in a more favorable position with the Russian space station. Two more space shuttle missions, using Spacehab modules, were flown to the *Mir* in FY 1996. The Space Acceleration Measurement System (SAMS) has continued to collect and record data to characterize the *Mir*'s microgravity environment and support the microgravity experiments manifested on that space station. The remainder of the microgravity experiment apparatus planned for the *Mir* was delivered to Russia for installation in the

Priroda module. This microgravity hardware included the glovebox; in collaboration with Canada, the Microgravity Isolation Mount (MIM); and biotechnology hardware to support PCG, and cell and tissue culture growth.

One of the first pieces of hardware launched was the Microgravity Glovebox (MGBX). This facility provides work space, filtration, video recording, lighting, and containment control capabilities to support a large array of on-orbit investigations. During the past year, the MGBX provided investigative resources to support two combustion experiments and three fluid physics experiments.

Extending the Microgravity Science Research Program's international cooperation efforts, the Canadian-sponsored MIM facility was included in the Program. This valuable piece of hardware was launched on an early flight and provided acceleration isolation for a U.S. fluid physics evaluation and a Canadian study of liquid metal diffusion.

New technology for protein crystal growth and bioreactors for cell tissue growth were tested, with the samples being exchanged during shuttle flights to the *Mir*. These technologies appear to be promising, based on 1996 work. Several methods of long-term crystallization were studied and a Biotechnology System (BTS) was installed and tested on orbit for the purpose of supporting biomedical research. This research facility later supported successful growth of three-dimensional structured cartilage tissue. Continued development is under way aboard the *Mir*.

The Microgravity Science Research Program continues to collect data and gain experience in conducting long-duration space flight operations and investigations. The knowledge and technique refinement acquired through various projects will optimize operations and science return planned for the *ISS*.

International Space Station

The *ISS* represents an unprecedented level of international cooperation and complexity. The Administration expanded the international scope of the *ISS* dramatically by forming a cooperative agreement with the Russian Space Agency (RSA). *ISS* team members now include NASA, RSA, ESA, CSA, the National Space Development Agency of Japan (NASDA), and the Italian Space Agency (ASI). Through FY 1996, CSA, ESA, and NASDA have invested nearly \$6 billion for design and development, and anticipate a total expenditure of \$10 billion.

The development of the *ISS* Program is laid out in three phases. Phase 1, which is currently under way, includes up to nine shuttle-*Mir* docking missions. Phase 2 begins with the launch of the U.S.-funded/Russian-built-and-launched Functional Cargo Block (FCB) in 1998, and includes limited science capabilities. Phase 3 completes the pressurized volume space and crew accommodations by integrating the international modules and the U.S. Habitation Module in 2002.

In FY 1996, NASA consolidated the management of *ISS* research and technology, science utilization, and payload development with the *ISS* Development and Operations Program in order to develop an integrated management structure for the program. The NASA HQ Office of Life and Microgravity Science and Applications (OLMSA) continues to be responsible for establishing the research requirements to be accommodated on the *ISS*.

During FY 1996, the BTF experiment control computer flew on the *Mir* to control cell and tissue culture experiments. The *Mir* precursor flights will reduce the risk in the design and development of full-facility operations for the *ISS*. NASA and ESA are examining ways to combine efforts in the research to understand the protein crystallization process. This may include sharing next-generation hardware on the *ISS*.

Preliminary talks began during 1996 to continue the ongoing cooperation in sharing shuttle hardware.

The combustion and fluids module scientists for the Fluids and Combustion Facility (FCF) completed their Requirements Definition Review in October 1996. After successful completion of the review, the facility proceeded to the preliminary design and development phase.

Advisory Groups

The Microgravity Science Research Program collaborated with, and received valuable guidance from, several advisory and review groups during FY 1996. Program content, plans, and priorities were reviewed periodically by the Microgravity Science and Applications Advisory Subcommittee, consisting of the chairs of the Microgravity Discipline Working Groups, PI's, and representatives from industry and academia. The Space Station Utilization Advisory Subcommittee, which includes technology and commercial representatives, continually reviews the program with regard to ISS utilization. Both are subcommittees of the Life and Microgravity Sciences and Applications Advisory Committee (LMSAAC), a committee of the NASA Advisory Council.

The science Discipline Working Groups for biotechnology, combustion science, fluids physics, and materials science continued the process of recommending discipline refinements and science priorities in FY 1996. The Discipline Working Groups are responsible for maintaining an overview of the efforts in the discipline areas and providing an annual program assessment. They are charged with identifying the most promising areas for scientific investigation and most advantageous approaches for experimentation. A fundamental physics steering group provided external advice related to the emerging microgravity fundamental physics research field.

NASA's MSAD requested that the Committee on Microgravity Research, a standing committee of the National Research Council's Space Studies Board, provide advice regarding the need for preserving and archiving microgravity data and samples. The committee issued its findings in the *Archiving Microgravity Flight Data and Samples* report published in March 1996. The report examined the rationale and methodologies for archiving microgravity flight samples and data and included the following recommendations:

- (1) The Microgravity Science Research Program should continue to use the Experiment Data Management Plan (EDMP) as the document that defines sample and data archiving requirements for each microgravity experiment.
- (2) The process of establishing a mutually agreeable EDMP should take place early in the mission planning process.
- (3) The EDMP process should be used to frame, answer, and then review the question of what portion of flight-generated samples will be retained by the investigator and what portion will be transferred to NASA for archiving.
- (4) The requirement for the submission of EDMP's should be described explicitly in each NRA.
- (5) EDMP format and content should be uniform across all the microgravity experiments sponsored by NASA.
- (6) EDMP's should be an item of discussion at each of the NASA science reviews at which peer review occurs. A tentative EDMP, developed jointly by the PI's and NASA project scientists, should be presented as early as the Science Requirements Review stage, and then subsequently amended at each of the following reviews.
- (7) NASA should take advantage of the growth in the Internet-based World Wide Web (WWW) to post EDMP's online for all its microgravity flight experiments.

Microgravity Research Conducted in FY 1996

In FY 1996, NASA funded a robust Microgravity Science Research Program in the five microgravity-related disciplines—biotechnology, combustion science, fluid physics, fundamental physics, and materials science. Experiments promoted deeper understanding of phenomena within a variety of scientific disciplines and often yielded interdisciplinary benefits. Investigations sponsored as part of this Program shared one characteristic—they all required reduced or near-zero-gravity conditions in order to achieve their objectives. FY 1996 highlights are presented below.

The overall Microgravity Science Research Program is conducted through integrated ground-based and flight programs. In addition to providing meaningful microgravity results as “stand-alone” programs, the ground-based research program also is used to develop concepts leading to flight experiments, determine limitations of various terrestrial processing techniques, and provide analysis and modeling support to the flight program. A successful ground-based research program generally represents a necessary first step toward flight experimentation.

Biotechnology

Overview

Biotechnology is broadly defined as any technology concerned with research on, manipulation of, and manufacture of biological molecules, tissues, and living organisms to produce or obtain products or perform functions. The NASA microgravity biotechnology program uses the advantage of the microgravity environment to aid in that research. The program is currently active in two major areas: (1) protein crystal growth (PCG) and (2) mammalian cell and tissue culture. In the first area, researchers seek to grow protein crystals suitable for structural analysis by x-ray diffraction and understand how these crystals form. In the second area, investigators study and evaluate the benefit of low gravity for growing cells and tissues. NASA's MSFC is the microgravity biotechnology management center, providing direct support for PCG research. NASA's Johnson Space Center (JSC) provides support for

research in cell and tissue culturing. NASA is also moving ahead with cooperative activities with the National Institutes of Health (NIH), as described in section 3 of this report.

Funding in biotechnology includes financial support for research centers at MIT and the Wistar Institute. A cooperative program between NASA and NIH also has been established for support of research utilizing bioreactor technology at NIH's Institute for Child Health and Human Development. Another NASA–NIH cooperative program, at NIH's Laboratory for Structural Biology, has been established to enhance laboratory-based protein crystallography. This effort strives to improve x-ray diagnostic technology and then transfer that technology to the U.S. biotechnology community.

In the area of PCG, academic, industrial, and Federal Government researchers, armed with advanced biotechnology techniques and

detailed data on the structure of key proteins, are creating a new generation of drugs. Researchers use data on the structure of proteins to design drugs at the molecular level that will interact with specific proteins and treat specific diseases. This approach promises to produce superior medicines for a wide range of conditions, replacing the trial-and-error approach to pharmaceutical development that has been the rule for centuries. Schering Plough (NJ); Eli Lilly (NJ); Upjohn (MI); Bristol-Myers Squibb (NJ); Smith Kline Beecham (PA); BioCryst (AL); DuPont Merck (DE); Eastman Kodak (NY); and Vertex (MA) are working with NASA and NASA-funded researchers to produce high-quality protein crystals for new drug development.

The first set of such drugs resulting from NASA-sponsored research have reached phase three of clinical trials, the last set of trials before a new drug can be approved for

general use. Although not all drugs successfully complete clinical trials, moving forward to this stage indicates progress in bringing NASA's research results to the general public. Scientists have used space shuttle missions to produce superior protein crystals for research on clinical conditions including cancer, diabetes, emphysema, influenza, and immune system disorders.

NASA also supported research on the recently released new generation of protease inhibitors used to treat HIV (the virus that causes AIDS). That research focused on the transport of the new drug throughout the human body. Finally, researchers working with NASA's MSFC are using microgravity to understand how protein crystals form and grow. This information will be used to improve the success rate of crystal growth in terrestrial laboratories across the United States. Specific examples of activities in the protein crystal growth area are:

- Dr. Lawrence J. DeLucas, O.D., Ph.D., of the University of Alabama in Birmingham Center for Macromolecular Crystallography, grew crystals of influenza neuraminidase with improved resolution over previously grown crystals, permitting additional x-ray diffraction data.
- Dr. Mark Wardell completed and refined the structure of human antithrombin III from crystals grown during 1995. The improvements in microgravity-grown crystals revealed new insights into the active site. The contributions of microgravity to this important research effort are clearly described in two manuscripts describing the results which were submitted in 1996. These papers are now in press in *Acta Crystallographica* and the *Journal of Molecular Biology*.
- Dr. Gerry Bunick and his research group grew crystals of the nucleosome core particle on STS-76 which were significantly larger than any previously obtained by any method. The highest resolution data sets for this

important fundamental research have been obtained from crystals produced in microgravity experiments.

Growing tissue samples—known as *tissue culturing*—is one of the fundamental goals of biomedical research; laboratory containers called *bioreactors* are used to grow, or “culture,” samples of body tissues. Of major importance, scientists could use cancer tumors and other tissues that are successfully grown outside the body to test and study treatments, such as chemotherapy, without risking harm to patients. Tissues from bioreactors will also offer important medical insights into how tissues grow and develop in the body. Highlights of recent research in this area include the following examples:

- Dr. John M. Jessup, Harvard University School of Medicine, has used the NASA bioreactor system to construct three-dimensional models of human colon cancer and has flown cancer cells in space to demonstrate the advantages of microgravity in promoting tissue assembly. These tumor models are invaluable in understanding the dynamic interactions that result in tumor growth and in establishing models for novel therapeutic strategies.
- Dr. Lisa Freed, MIT, was the PI for the longest continuous cell culture in space (more than 140 days), wherein cartilage tissue was propagated in a NASA bioreactor to demonstrate the advantages of microgravity in engineering cartilage. It is anticipated that this approach will advance our ability to engineer replacement cartilage for transplants.
- Dr. Joshua Zimmerberg and Dr. Leonid Margolis, NIH, are using the NASA ground-based bioreactor system to assemble lymphoid cell constructs to investigate the pathogenesis of the HIV virus.

Meetings, Awards, and Publications

NASA Biotechnology Cell Science and Protein Crystal Growth investigators conducted a symposium at the International Congress of the Society of In Vitro Biology on June 25, 1996, in San Francisco, CA. The Program Manager for Cell Science was an invited plenary lecturer for the International Cellular Transplant Society annual meeting in Miami, FL, on September 29–October 2, 1996.

The NASA Protein Crystal Conference was held in Panama City, FL, on April 28–30, 1996. This meeting addressed fundamental questions in protein crystallization for both flight and ground-based experiments. There were approximately 20 presentations from NASA and international investigators.

The International Workshop on Microgravity Biotechnology for the *International Space Station* took place at the University of California, Riverside (UCR), on February 15–16, 1996. The goal of the workshop was to bring together international partners to coordinate and communicate the types of flight hardware and experiments under consideration for the *ISS*. Agencies represented included NASA, the Canadian Space Agency (CSA), the German Space Agency (DARA), ESA, NASDA, and the French National Center for Space Studies (CNES). Along with the presentations and discussions of Agency plans, the workshop included a tour of UCR protein crystallography facilities, conducted by microgravity PI Dr. Alexander McPherson, Jr.

Dr. McPherson published a paper on the results from the first flights of flash-frozen protein samples on the *Mir*. This paper showed that the innovative use of this crystallization technique could potentially allow for inexpensive deployment of large numbers of samples for determination of optimum crystallization conditions.

Flight Experiments

Increment 4 of the NASA/Mir program hosted the first long-term tissue culture experiment in space. Dr. Freed is conducting research on the engineering of cartilage for research and transplanting. Bovine chondrocytes were assembled in ground-based reactors and transitioned to a space bioreactor flown to the *Mir* on STS-79. On Earth, the NASA bioreactor supports tissue growth up to 1 centimeter, whereas microgravity may afford growth beyond this limit. Early results suggest that the cartilage returned in a healthy, viable state and were spherical, while the ground controls were

small disks. Critical physical and biological analysis will determine the unique aspects of cartilage development in space.

The PCG project flew 13 instruments during 1996. Those instruments contained more than 2,000 individual samples of a total of 69 different proteins. Evaluation of the flight results from these experiments is in varying stages, depending on the flight date. Structural data returned from these flights will be used to begin or augment the process of designing drugs to attack diseases in the area of research. As a result of those flights and flights in previous years, more than 25 scientific papers were published and more

than 60 citations of previous papers were reported in 1996. These papers represent the key method of communicating the results of NASA's PCG research to the scientific research community. Citations of previous papers are an indication of the usefulness of the research results, as other scientists use the information revealed in the original work.

The FY 1996 biotechnology ground and flight tasks are listed in table 2. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1996*, NASA Technical Memorandum 4780, March 1997.

TABLE 2.—*Biotechnology tasks funded by MSAD in FY 1996 (includes no-cost extensions).*

Flight Experiments

Protein Crystal Growth Vapor-Diffusion

Flight Hardware and Facility

Dr. Daniel C. Carter
NASA MSFC
Marshall Space Flight Center, AL

Protein Crystal Growth in Microgravity

Dr. Lawrence J. DeLucas
University of Alabama, Birmingham
Birmingham, AL

Electrophoretic Separation of Cells and Particles From Rat Pituitary

Dr. Wesley C. Hymer
Pennsylvania State University
University Park, PA

Growth, Metabolism, and Differentiation of MIP-01 Carcinoma Cells

Dr. John M. Jessup
Harvard Medical School
Boston, MA

Membrane Transport Phenomena

Mr. Larry W. Mason
Lockheed Martin Astronautics
Denver, CO

An Observable Protein Crystal Growth Flight Apparatus

Dr. Alexander McPherson, Jr.
University of California, Riverside
Riverside, CA

Enhanced Dewar Program

Dr. Alexander McPherson, Jr.
University of California, Riverside
Riverside, CA

Investigation of Protein Crystal Growth Mechanisms in Microgravity

Dr. Keith B. Ward
Naval Research Laboratory
Washington, DC

Ground-Based Experiments

The Use of Bioactive Glass Particles as Microcarriers in Microgravity Environment

Prof. Portonovo S. Ayyaswamy
University of Pennsylvania
Philadelphia, PA

Evaluation of Ovarian Tumor Cell Growth and Gene Expression

Dr. Jeanne L. Becker, Ph.D.
University of South Florida
Tampa, FL

Expansion and Differentiation of Cells in Three-Dimensional Matrices Mimicking Physiological Environments

Prof. Rajendra S. Bhatnagar
University of California, San Francisco
San Francisco, CA

Quantitative, Statistical Methods for Pre-Flight Optimization, and Post-Flight Evaluation of Macromolecular Crystal Growth

Dr. Charles W. Carter
University of North Carolina, Chapel Hill
Chapel Hill, NC

Microgravity Simulated Prostate Cell Culture

Prof. Leland W. Chung
University of Virginia
Charlottesville, VA

Noninvasive Near-Infrared Sensor for Continual Cell Glucose Measurement

Dr. Gerard L. Cote
Texas A&M University
College Station, TX

A Comprehensive Investigation of Macromolecular Transport During Protein Crystallization

Dr. Lawrence J. DeLucas
University of Alabama, Birmingham
Birmingham, AL

Development of Robotic Techniques for Microgravity Protein Crystal Growth

Dr. Lawrence J. DeLucas
University of Alabama, Birmingham
Birmingham, AL

Macromolecular Crystallization: Physical Principles, Passive Devices, and Optimal Protocols

Dr. George T. DeTitta
Hauptman-Woodward Medical
Research Institute
Buffalo, NY

The Effect of Microgravity on the Human Skin Equivalent

Dr. S. D. Dimitrijevic
University of N. Texas Health
Science Center, Fort Worth
Fort Worth, TX

Use of Microgravity-Based Bioreactors to Study Intercellular Communication in Airway Cells

Dr. Ellen R. Dirksen
University of California, Los Angeles
Los Angeles, CA

Microgravity Thresholds for Anti-Cancer Drug Production on Conifer Cells

Dr. Don J. Durzan
University of California, Davis
Davis, CA

Laser Scattering Tomography for the Study of Defects in Protein Crystals

Dr. Robert S. Feigelson
Stanford University
Stanford, CA

Role of Fluid Shear on 3-D Bone Tissue Culture

Prof. John A. Frangos
University of California, San Diego
La Jolla, CA

Microgravity Studies of Cell-Polymer Cartilage Implants

Dr. Lisa E. Freed, M.D., Ph.D.
Massachusetts Institute of Technology
Cambridge, MA

Microgravity Tissue Engineering

Dr. Lisa E. Freed, M.D., Ph.D.
Massachusetts Institute of Technology
Cambridge, MA

Protein and DNA Crystal Lattice Engineering

Dr. D.T. Gallagher
Center for Advanced Research in
Biotechnology
Rockville, MD

Microgravity-Based Three-Dimensional Transgenic Cell Models

Dr. Steve R. Gonda, Ph.D.
NASA JSC
Houston, TX

Lymphocyte Invasion Into Tumor Models Emulated Under Microgravity Conditions In Vitro

Mr. Thomas J. Goodwin, M.S.
NASA JSC
Houston, TX

Differentiation of Cultured Normal Human Renal Epithelial Cells in Microgravity

Dr. Timothy G. Hammond
Tulane University
New Orleans, LA

Excitable Cells and Growth Factors Under Microgravity Conditions

Dr. Charles R. Hartzell
Alfred I. DuPont Institute
Wilmington, DE

Determining the Conditions Necessary for the Development of Functional Replacement Cartilage Using a Microgravity Reactor

Prof. Carole A. Heath
Iowa State University
Ames, IA

The Effects of Microgravity on Viral Replication

Dr. John H. Hughes, Ph.D.
Ohio State University
Columbus, OH

Sensitized Lymphocytes for Tumor Therapy Grown in Microgravity

Dr. Marylou Ingram
Huntington Medical Research Institutes
Pasadena, CA

Three-Dimensional Tissue Interactions in Colorectal Cancer Metastasis

Dr. John M. Jessup
New England Deaconess Hospital
Boston, MA

Use of Rotating Wall Vessel (RWV) to Facilitate Culture of Norwalk Virus

Dr. Philip Johnson, M.D.
University of Texas Medical School at Houston
Houston, TX

Fibril Formation by Alzheimer's Disease Amyloid in Microgravity

Dr. Daniel A. Kirschner
Boston College
Chestnut Hill, MA

Applications of Atomic Force Microscopy to Investigate Mechanisms of Protein Crystal Growth

Dr. John H. Konnert
National Research Laboratories
Washington, DC

Regulation of Skeletal Muscle Development and Differentiation In Vitro by Mechanical and Chemical Factors

Dr. William E. Kraus
Duke University Medical Center
Durham, NC

Neuro-Endocrine Organoid Assembly In Vitro

Dr. Peter I. Lelkes
University of Wisconsin, Milwaukee
Milwaukee, WI

Multidisciplinary Studies of Cells, Tissues, and Mammalian Development in Simulated Microgravity

Prof. Elliot M. Levine
The Wistar Institute
Philadelphia, PA

Analysis of Electrophoretic Transport of Macromolecules Using Pulsed Field Gradient NMR

Dr. Bruce R. Locke
Florida State University
Tallahassee, FL

Ground-Based Program for the Physical Analysis of Macromolecular Crystal Growth

Dr. Alexander J. Malkin
University of California, Riverside
Riverside, CA

***Thyroid Follicle Formation in Microgravity:
Three-Dimensional Organoid Construction
in a Low-Shear Environment***

Dr. Andreas Martin, M.D.
Mount Sinai School of Medicine
New York, NY

Biological Particle Separation in Low Gravity

Dr. D. J. Morré
Purdue University
West Lafayette, IN

***Continuous, Noninvasive Monitoring
of Rotating Wall Vessels and Application
to the Study of Prostate Cancer***

Prof. David W. Murhammer
University of Iowa
Iowa City, IA

***Insect-Cell Cultivation in Simulated
Microgravity***

Prof. Kim O'Connor
Tulane University
New Orleans, LA

***Shear Sensitivities of Human Bone Marrow
Cultures***

Dr. Bernhard O. Palsson
University of California, San Diego
La Jolla, CA

***Microgravity and Immunosuppression: A
Ground-Based Model in the Slow Turning
Lateral Vessel Bioreactor***

Dr. Neal R. Pellis
NASA JSC
Houston, TX

***Microgravity Crystallization
of Avian Egg White Ovostatin***

Dr. Marc L. Pusey
NASA MSFC
Marshall Space Flight Center, AL

***Isolation of the Flow, Growth and Nucleation
Rate, and Microgravity Effects on Protein
Crystal Growth***

Dr. Marc L. Pusey
NASA MSFC
Marshall Space Flight Center, AL

Stem Cell Expansion in Rotating Bioreactors

Dr. Peter J. Quesenberry
University of Massachusetts
Worcester, MA

***Study of Crystallization and Solution
Properties of Redesigned Protein Surfaces***

Dr. David C. Richardson
Duke University Medical Center
Durham, NC

***Convective Flow Effects on Protein Crystal
Growth and Diffraction Resolution***

Prof. Franz E. Rosenberger
University of Alabama, Huntsville
Huntsville, AL

***Nucleation and Convection Effects
in Protein Crystal Growth***

Prof. Franz E. Rosenberger
University of Alabama, Huntsville
Huntsville, AL

***Enhancement of Cell Function in Culture
by Controlled Aggregation
Under Microgravity Conditions***

Prof. W.M. Saltzman
Cornell University
Ithaca, NY

***Robotic Acquisition and Cryogenic Preservation
of Single Crystals of Macromolecules
for X-Ray Diffraction***

Dr. Craig D. Smith
University of Alabama, Birmingham
Birmingham, AL

***Influence of Microgravity Conditions on Gene
Transfer Into Expanded Populations of Human
Hematopoietic Stem Cells***

Dr. F.M. Stewart
University of Massachusetts
Worcester, MA

***Mechanisms for Membrane Protein
Crystallization: Analysis by Small Angle
Neutron Scattering***

Dr. David M. Tiede
Argonne National Laboratory
Argonne, IL

Preparation and Analysis of RNA Crystals

Dr. Paul Todd
University of Colorado, Boulder
Boulder, CO

***Development of Microflow Biochemical Sensors
for Space Biotechnology***

Dr. Bruce Towe
Arizona State University
Tempe, AZ

***Experimental Studies of Protein Crystal Growth
Under Simulated Low-Gravity Conditions***

Dr. Eugene H. Trinh
NASA JPL
Pasadena, CA

***Two-Dimensional Protein Crystallization
at Interfaces***

Dr. Viola Vogel
University of Washington
Seattle, WA

***Automation of Protein Crystallization
Experiments: Crystallization by Dynamic
Control of Temperature***

Dr. Keith B. Ward
National Research Laboratories
Washington, DC

***Thermal Optimization of Growth
and Quality of Protein Crystals***

Dr. John M. Wienczek
University of Iowa
Iowa City, IA

***Search for a Dilute Solution Property
to Predict Protein Crystallization***

Dr. W.W. Wilson
Mississippi State University
Mississippi State, MS

***A Rational Approach for Predicting
Protein Crystallization***

Dr. W.W. Wilson
Mississippi State University
Mississippi State, MS

***Phase Shifting Interferometric Analysis
of Protein Crystal Growth Boundaries
and Convective Flows***

Dr. William K. Witherow
NASA MSFC
Marshall Space Flight Center, AL

***Characterization of Solvation Potentials
Between Small Particles***

Dr. Charles E. Zukoski
University of Illinois, Urbana-Champaign
Urbana, IL

Combustion Science

Overview

The Microgravity Combustion Research Program currently includes research in the areas of premixed gas flames, gaseous diffusion flames, droplet/spray combustion, surface combustion, smoldering, and combustion synthesis. In addition, a number of advanced diagnostic instrumentation technologies are being developed for various experimental studies in the limited confines available for most microgravity experiments.

In the area of premixed gas combustion, NASA supports experimental and modeling studies of the effects of gravity on flammability limits, flame stability and extinction, low-flow turbulent flames, and laminar flame structure and shape. Modeling activities include simplified analytical approaches aimed at elucidating mechanisms and detailed numerical analysis aimed at quantifying them. To date, several discoveries, all important to hazard control and basic combustion science and made possible only via microgravity experiments, have been made in this area. Activities in the area of gaseous diffusion flames include study of the effects of gravity on soot formation, relationships between chemical kinetic time scales and flow time scales, flammability limits and burning rates, and structure of gas-jet diffusion flames.

In the area of combustion of fuel droplets, particles, and sprays, research includes examining combustion of single-component and multicomponent spherical droplets, as well as ordered arrays of fuel droplets and sprays for improved understanding of the interactions of combustion of individual droplets in sprays. Several new droplet combustion phenomena have been revealed in drop tower microgravity testing; these are expected to lead to major improvements in design of combustors utilizing liquid fuels.

In addition, NASA supported several experimental and analytical studies of the

spread of flames across solid- and liquid-fuel surfaces, both in quiescent oxidizer environments and with low-velocity flows; benefits here lie mainly in the area of fire safety. Experimental and analytical studies of smoldering combustion, which should have significant impact on prevention of unwanted fires both on the ground and in space, are also supported.

Collaborative research between Japan/New Energy and Industrial Technology Development Organization (NEDO) and the United States/NASA was established and conducted successfully in the Japanese 10-second drop tower and NASA LeRC's 2.2- and 5-second drop towers for investigations of fuel droplets and solid fuel burning. This collaborative research saved substantial resources for each country, by avoiding duplicative construction of hardware, while gaining new scientific knowledge on these phenomena.

A relatively new area of combustion science is the combustion synthesis of materials; one subcategory of particular interest is referred to as self-deflagrating high-temperature synthesis. Gravity fields can have major impact on this process, through buoyancy-induced flow effects on heat transport processes and through gravity-driven flow of liquid-phase intermediates through a porous solid matrix prior to cool-down/freezing of the product behind the reaction front. Since the crystal morphology of the final product (which strongly affects its properties) tends to be very sensitive to the temperature-time history seen during the passing of the self-deflagrating high-temperature synthesis combustion wave, these gravity-dependent effects can have major effects on the product produced.

To date, the work in microgravity combustion has demonstrated major differences in structures of various types of flames from that seen in normal gravity. Besides the

practical implications of these results to combustion efficiency (energy conservation), pollutant control (environmental considerations), and flammability (fire safety), these studies establish that better mechanistic understanding of individual processes making up the overall combustion process can be obtained by comparing the results gathered in microgravity versus normal gravity tests.

On May 14, 1996, a patent entitled "Apparatus and Method for Burning a Lean Premixed Fuel/Air Mixture with Low NO_x Emission" was awarded to researchers at the Lawrence Berkeley National Laboratory, under contract to NASA LeRC, for the performance of microgravity combustion science research into a new method to lower pollutant emissions and increase efficiency in natural-gas appliances such as residential heating furnaces and hot water heaters. Burners with their "ring flame stabilizer" reduce significantly the emissions of nitrogen oxides (NO_x) that are major contributors to smog and atmospheric contamination. In a test on a home furnace, the ring flame stabilizer reduced the amount of pollutants released by 90 percent, and at the same time improved energy efficiency by 2 percent. From both an environmental and economic standpoint, these values are significant.

Examples of spinoff technologies developed in this project include:

- Under NASA funding, Dr. Joel Silver and coworkers at Southwest Sciences, Inc., developed a High Frequency Modulated Line Absorption Spectroscopy system for the nonintrusive, nonperturbative measurement of methane, water vapor, and temperature in microgravity flames. This technology has

been licensed and an ammonia monitor for industrial and electric utility power plants developed and marketed; instruments for other stack gases are currently under development.

- In conducting microgravity experiments on wrinkled laminar flames in the NASA/LeRC drop towers, Dr. Robert Cheng and Dr. Larry Kostiuk, of the Lawrence Berkeley Laboratory, discovered that a metal ring placed above the fuel nozzle could stabilize a fuel-lean flame, leading to the capability for burning fuels at air/fuel ratios that result in significant reduction of NO_x emissions, of major importance in regards to combustion-generated air pollution.
- Soot and polycyclic aromatic hydrocarbons arise through fuel pyrolysis reactions common to all combustion processes. Several polycyclic aromatic hydrocarbons and soot are known or suspected carcinogenic or mutagenic agents. By using advanced optical diagnostics such as laser-induced fluorescence and laser-induced incandescence, these by-products may be detected within combustion processes, with determination of the evolution of soot formation proceeding from gaseous molecular fragments to solid carbon-like soot readily visualized. Such data can critically test soot control strategies.
- Knowledge of the soot concentration in combustion exhaust gases (such as from cars or power plants) is important to several devices such as engines or combustors. In other applications involving soot reduction strategies, the spatial distribution of soot, important for assessing mixing processes or flow uniformity, is required. Recently, the applicability

of laser-induced incandescence for measuring soot in post-combustion exhaust was demonstrated using a laboratory-scale chimney designed to simulate a soot-laden exhaust stream.

In FY 1996, NASA made awards to 17 proposing academic, industrial, and Governmental institutions for microgravity combustion science investigations. The awards range from basic scientific research to the development of advanced instrumentation that will be of use not only to the microgravity research community, but to terrestrial research and applications as well. New topical areas include the study of flame-synthesized fullerenes in microgravity (the material for which the Nobel Prize in Chemistry was recently awarded) and metals combustion in microgravity. Research in these areas will be conducted for the next 4 years, with extensive utilization of NASA's drop towers and low-gravity aircraft to perform microgravity experimentation.

In addition to these ground-based investigations, NASA awarded grants to three new proposers for spaceflight experimentation in microgravity combustion science. These involve the development of testing methodology and apparatus for categorizing the flammability of spacecraft materials in microgravity; the study of multicomponent fuel droplets; and the study of so-called "cool flames," applicable to internal combustion engine performance. The definition of these experiments and subsequent peer reviews for approval for spaceflight will take place over the next few years.

Meetings, Awards, and Publications

The 26th International Symposium on Combustion, the most prestigious gathering of the combustion science community, was held in Naples, Italy, during the week of July 28–August 2, 1996. At the symposium, 29 papers were presented by NASA-funded microgravity combustion science researchers, making up nearly 10 percent of the papers

presented at this biennial international meeting. Also at the meeting, Prof. William Sirignano, Spread Across Liquids (SAL) co-investigator, was awarded the Combustion Institute's Gold Medal for Lifetime Achievement.

Enterprise scientist Dr. Merrill King chaired the Microgravity Combustion Session of the 10th Microgravity Science and Space Processing Symposium held at the American Institute of Aeronautics and Astronautics (AIAA) 34th Aerospace Sciences Meeting in Reno, NV, January 15–18, 1996.

NASA participated in the Space '95 conference in Japan in October 1995. An overview of the NASA combustion science program was presented. NASA officials also visited Japanese microgravity drop towers at Hokkaido and Nagoya.

Flight Experiments

The microgravity combustion science program had a very productive year, with successful investigations being performed in half of the research topical areas and on all available carriers.

The Diffusive and Radiative Transport in Fires (DARTFire) experiment flew for the first of three planned tests on a sounding rocket, investigating flame initiation, fire spread, and post-spread steady-state combustion of a thick solid-fuel sample under various low-speed oxidizer flows. Small amounts of radiant heating were imposed on the fuel sample to determine if this kind of assisted heating of the fuel sample will enable the flame to survive and spread. This was the first experimental control and measurement of radiative heating in a microgravity combustion experiment. It is also realistic in the sense that nearby burning material provides radiant heating in both practical and accidental fires.

The third of the planned sounding rocket tests of the SAL experiment was flown in March 1996. All three flights were highly

successful, revealing new flame-spread behavior attributable to the absence of gravitational effects and also proving the feasibility in microgravity of several novel, advanced diagnostics and fluid management technologies. Even with forced air velocities of the same order of magnitude as that induced naturally by buoyancy in normal gravity, the flame behavior in microgravity was found to be completely different. Based on these results, an additional five flights were approved to verify hypotheses that attempt to explain some of the aforementioned, surprising behaviors.

Three combustion investigations were performed on the USMP-3 mission in February/March 1996, in order to begin to directly address on-orbit safety of the crew from accidental fire. The Radiative Ignition and Transition to Spread Investigation and the Forced Flow Flamespread Test (FFFT) studied the transition from a momentary ignition to a fire spread situation. From a scientific perspective these were highly successful, as they identified new and

unpredicted behavior. The third investigation, Comparative Soot Diagnostics, provided the first test data on the in-space performance of the space shuttle and the ISS smoke detection systems, while determining particulate sizes and concentrations from the combustion of typical spacecraft materials and a selected hydrocarbon fuel.

The first combustion experiments were flown on the *Mir* space station throughout the summer of 1996. Within the Candle Flames in Microgravity glovebox apparatus, candles burned for many minutes in the *Mir* environment and appear to have answered long standing questions about whether a quiescent diffusion flame can persist in microgravity. In addition, using the FFFT apparatus, solid fuel samples were burned in various oxidizer flows to provide some of the first data on flame spread over thick fuels. A follow-on experiment involving solid fuel samples was developed and is planned for flight on the *Mir* in 1997.

The Fiber Supported Droplet Combustion investigation, conceived to study fundamental phenomena related to liquid fuel droplet combustion in air, flew on USML-2 in October/November 1995. A major portion of the energy produced in the world today comes from burning liquid hydrocarbon fuels in the form of a spray of droplets. A detailed understanding of the fundamental physical processes involved in droplet combustion is important not only in energy production, but also in propulsion, reduction of combustion-generated pollution, and controlling fire hazards when handling liquid combustibles. These experiments were the first to study large isolated single droplets with and without forced air convection.

The FY 1996 ground and flight tasks for combustion science are listed in table 3. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1996*, NASA Technical Memorandum 4780, March 1997.

TABLE 3.—Combustion science tasks funded by MSAD in FY 1996 (includes no-cost extensions).

Flight Experiments

Scientific Support for an Orbiter Middeck Experiment on Solid Surface Combustion
Prof. Robert A. Altenkirch
Washington State University
Pullman, WA

Low-Velocity, Opposed-Flow Flame Spread in a Transport-Controlled, Microgravity Environment
Prof. Robert A. Altenkirch
Washington State University
Pullman, WA

Reflight of the Solid Surface Combustion Experiment With Emphasis on Flame Radiation Near Extinction
Prof. Robert A. Altenkirch
Washington State University
Pullman, WA

Gravitational Effects on Laminar, Transitional, and Turbulent Gas-Jet Diffusion Flames
Dr. M.Y. Bahadori
Science Applications International Corporation
Torrance, CA

Sooting and Radiation Effects in Droplet Combustion
Prof. Mun Y. Choi
University of Illinois, Chicago
Chicago, IL

Candle Flames in Microgravity
Dr. Daniel L. Dietrich
NASA LeRC
Cleveland, OH

Investigation of Laminar Jet Diffusion Flames in Microgravity: A Paradigm for Soot Processes in Turbulent Flames
Prof. Gerard M. Faeth
University of Michigan
Ann Arbor, MI

Unsteady Diffusion Flames: Ignition, Travel, and Burnout
Dr. Frank Fendell
TRW
Redondo Beach, CA

Fundamental Study of Smoldering Combustion in Microgravity
Prof. A.C. Fernandez-Pello
University of California, Berkeley
Berkeley, CA

Flammability Diagrams of Combustible Materials in Microgravity
Prof. A.C. Fernandez-Pello
University of California, Berkeley
Berkeley, CA

Ignition and the Subsequent Transition to Flame Spread in Microgravity
Dr. Takashi Kashiwagi
National Institute of Standards and Technology
Gaithersburg, MD

The High-Lewis Number Diffusive-Thermal Instability in Premixed Gas Combustion and Low Temperature Hydrocarbon Oxidation and Cool Flames

Dr. Howard G. Pearlman
University of Southern California
Cleveland, OH

Studies of Premixed Laminar and Turbulent Flames at Microgravity

Prof. Paul D. Ronney
University of Southern California
Los Angeles, CA

Ignition and Flame Spread of Liquid Fuel Pools

Dr. Howard D. Ross
NASA LeRC
Cleveland, OH

Combustion Experiments in Reduced Gravity With Two-Component Miscible Droplets

Prof. Benjamin D. Shaw
University of California, Davis
Davis, CA

Combustion of Solid Fuel in Very Low Speed Oxygen Streams

Prof. James S. T'ien
Case Western Reserve University
Cleveland, OH

Droplet Combustion Experiment

Prof. Forman A. Williams
University of California, San Diego
La Jolla, CA

Ground-Based Experiments

Effects of Energy Release on Near Field Flow Structure of Gas Jets

Prof. Ajay K. Agrawal
University of Oklahoma
Norman, OK

Radiant Extinction of Gaseous Diffusion Flames

Prof. Arvind Atreya
University of Michigan
Ann Arbor, MI

Multicomponent Droplet Combustion in Microgravity: Soot Formation, Emulsions, Metal-Based Additives, and the Effect of Initial Droplet Diameter

Prof. C.T. Avedisian
Cornell University
Ithaca, NY

Gas-Phase Combustion Synthesis of Metal and Ceramic Nano-Particles

Prof. Richard L. Axelbaum
Washington University
St. Louis, MO

Development of Advanced Diagnostics for Characterization of Burning Droplets in Microgravity

Dr. William D. Bachalo
Aerometrics, Inc.
Sunnyvale, CA

Ignition and Combustion of Bulk Metals in Microgravity (Ground-Based Experiment)

Prof. Melvyn C. Branch
University of Colorado, Boulder
Boulder, CO

Modeling of Microgravity Combustion Experiments—Phase II

Prof. John D. Buckmaster
University of Illinois, Urbana-Champaign
Urbana, IL

A Numerical Model for Combustion of Bubbling Thermoplastic Materials in Microgravity

Dr. Kathryn M. Butler
National Institute of Standards and Technology
Gaithersburg, MD

Heterogeneous Combustion of Porous Solid Fuel Particles Under Microgravity: A Comprehensive Theoretical and Experimental Study

Prof. H.K. Chelliah
University of Virginia
Charlottesville, VA

Buoyancy Effects on the Structure and Stability of Burke-Schumann Diffusion Flames

Prof. L.-D. Chen
University of Iowa
Iowa City, IA

Gravitational Effects on Premixed Turbulent Flames: Microgravity Flame Structures

Dr. Robert K. Cheng
Lawrence Berkeley Laboratory
Berkeley, CA

Combustion of Interacting Droplet Arrays in a Microgravity Environment

Dr. Daniel L. Dietrich
NASA LeRC
Cleveland, OH

Internal and Surface Phenomena in Heterogeneous Metal Combustion

Dr. Edward L. Dreizin
AeroChem Research Laboratories, Inc.
Princeton, NJ

Interaction of Burning Metal Particles

Dr. Edward L. Dreizin
AeroChem Research Laboratories, Inc.
Princeton, NJ

Flame-Vortex Interactions Imaged in Microgravity

Prof. James F. Driscoll
University of Michigan
Ann Arbor, MI

Aerodynamic, Unsteady, Kinetic, and Heat Loss Effects on the Dynamics and Structure of Weakly-Burning Flames in Microgravity

Prof. Fokion N. Egolfopoulos
University of Southern California
Los Angeles, CA

Detailed Studies on the Structure and Dynamics of Reacting Dusty Flows at Normal and Microgravity

Prof. Fokion N. Egolfopoulos
University of Southern California
Los Angeles, CA

Effects of Gravity on Sheared and Nonsheared Turbulent Nonpremixed Flames

Prof. Said E. Elghobashi
University of California, Irvine
Irvine, CA

Soot Processes in Freely-Propagating Laminar Premixed Flames

Prof. Gerard M. Faeth
University of Michigan
Ann Arbor, MI

Combustion of Electrostatic Sprays of Liquid Fuels in Laminar and Turbulent Regimes

Prof. Alessandro Gomez
Yale University
New Haven, CT

Characteristics of Non-Premixed Turbulent Flames in Microgravity

Dr. Uday Hegde
NYMA, Inc.
Cleveland, OH

Three-Dimensional Flow in a Microgravity Diffusion Flame

Prof. Jean R. Hertzberg
University of Colorado, Boulder
Boulder, CO

Combustion Synthesis of Fullerenes and Fullerene Nanostructures in Microgravity

Prof. Jack B. Howard
Massachusetts Institute of Technology
Cambridge, MA

Unsteady Numerical Simulations of the Stability and Dynamics of Flames in Microgravity

Dr. K. Kailasanath
National Research Laboratories
Washington, DC

Real Time Quantitative 3-D Imaging of Diffusion Flame Species

Dr. Daniel J. Kane
Southwest Sciences, Inc.
Santa Fe, NM

Soot and Radiation Measurements in Microgravity Turbulent Jet Diffusion Flames

Prof. Jerry C. Ku
Wayne State University
Detroit, MI

Studies of Flame Structure in Microgravity

Prof. Chung K. Law
Princeton University
Princeton, NJ

Chemical Inhibitor Effects on Diffusion Flames in Microgravity

Dr. Gregory T. Linteris
National Institute of Standards and Technology
Gaithersburg, MD

Computational and Experimental Study of Laminar Diffusion Flames in a Microgravity Environment

Prof. Marshall B. Long
Yale University
New Haven, CT

Dynamics of Liquid Propellant Combustion at Reduced Gravity

Dr. Stephen B. Margolis
Sandia National Laboratories
Livermore, CA

Structure and Dynamics of Diffusion Flames in Microgravity

Prof. Moshe Matalon
Northwestern University
Evanston, IL

Filtration Combustion for Microgravity Applications: (1) Smoldering, (2) Combustion Synthesis of Advanced Materials

Prof. Bernard J. Matkowsky
Northwestern University
Evanston, IL

Combustion of PTFE: The Effect of Gravity on Ultrafine Particle Generation

Prof. J.T. McKinnon
Colorado School of Mines
Golden, CO

Premixed Turbulent Flame Propagation in Microgravity

Prof. Suresh Menon
Georgia Institute of Technology
Atlanta, GA

Gravitational Influences on Flame Propagation Through Non-Uniform Premixed Gas Systems

Dr. Fletcher J. Miller
Case Western Reserve University
Cleveland, OH

A Fundamental Study of the Combustion Syntheses of Ceramic-Metal Composite Materials Under Microgravity Conditions—Phase II

Prof. John J. Moore
Colorado School of Mines
Golden, CO

Stretched Diffusion Flames in Von Karman Swirling Flows

Dr. Vedha Nayagam
Analex Corporation
Brook Park, OH

Flow and Ambient Atmosphere Effects on Flame Spread at Microgravity

Prof. Paul D. Ronney
University of Southern California
Los Angeles, CA

Flammability Limits and Flame Dynamics of Spherical Flames in Homogeneous and Heterogeneous Mixtures

Prof. Paul D. Ronney
University of Southern California
Los Angeles, CA

Combustion Research

Dr. Howard D. Ross
NASA LeRC
Cleveland, OH

Combustion of Unconfined Droplet Clusters in Microgravity

Dr. Gary A. Ruff
Drexel University
Philadelphia, PA

Reduced Gravity Combustion With 2-Component Miscible Droplets

Prof. Benjamin D. Shaw
University of California, Davis
Davis, CA

Quantitative Measurement of Molecular Oxygen in Microgravity Combustion

Dr. Joel A. Silver
Southwest Sciences, Inc.
Santa Fe, NM

*Numerical Modeling of Flame-Balls
in Fuel-Air Mixtures*

Prof. Mitchell D. Smooke
Yale University
New Haven, CT

*Combustion of Rotating Spherical Premixed
and Diffusion Flames in Microgravity*

Dr. Siavash H. Sohrab
Northwestern University
Evanston, IL

*Diffusion Flame Structure, Shape and Extinction:
Geometrical Considerations*

Prof. Jose L. Torero
University of Maryland
College Park, MD

*Interactions Between Flames on Parallel Solid
Surfaces*

Dr. David L. Urban
NASA LeRC
Cleveland, OH

*Gasless Combustion Synthesis From Elements
Under Microgravity: A Study of Structure-
Formation Processes*

Prof. Arvind Varma
University of Notre Dame
Notre Dame, IN

*Studies of Wind-Aided Flame Spread Over
Thin Cellulosic Fuels in Microgravity*

Prof. Indrek S. Wichman
Michigan State University
East Lansing, MI

High-Pressure Combustion of Binary Fuel Sprays

Prof. Forman A. Williams
University of California, San Diego
La Jolla, CA

*Laser Diagnostics for Fundamental Microgravity
Droplet Combustion Studies*

Dr. Michael Winter
United Technologies Research Center
East Hartford, CT

*Combustion of a Polymer (PMMA) Sphere
in Microgravity*

Dr. Jiann C. Yang
National Institute of Standards and Technology
Gaithersburg, MD

Fluid Physics

Overview

Fluid physics is the study of properties and motion of fluids (liquids and gases) and the effects of such motion. Fluid motions are responsible for most transport and mixing that take place in the environment, in industrial processes, in vehicles, and in living organisms. The ultimate goal of research in fluid physics is to improve our ability to predict and control the behavior of fluids in all of the above situations, so as to improve our ability to design devices and to regulate them. Fluid motion involved in most situations is strongly influenced by gravity. The reduced-gravity environment of space offers a powerful research tool for the fluid physicist, enabling the observation and control of fluid phenomena in ways not possible on Earth.

The primary objective of the microgravity fluid physics program is to utilize the reduced-gravity environment to provide new insight into phenomena that are otherwise masked or confounded by the effects of Earth's gravity. Through a rigorous peer review process, 84 researchers were

selected to receive grants as a part of the 1994 fluid physics NRA process. These awards total over \$32 million, over more than a 4-year period, and include 71 ground-based and 13 flight-experiment definition studies. A listing of all the fluid physics grants, along with their PI's, is given in table 4. These grants cover the broad field of fluid physics, including the areas of capillary phenomena, contact-line dynamics, colloid physics, complex fluids, thermocapillary and solutocapillary phenomena, bubble or droplet migration and interaction, coalescence and aggregation, multiphase flows and phase change, electrokinetics and electrochemistry, biofluid mechanics, and measurement of equilibrium and transport properties of fluids.

Some of the highlights of the FY 1996 fluid physics research conducted in space, as well as in ground-based laboratories, are discussed below.

Physicists study the behavior of colloidal crystals to gain understanding of processes

involved in growth of atomic crystals that can lead to development of novel materials. In their experiments on the formation of colloidal crystals conducted aboard the USML-2 space shuttle mission, co-investigators Prof. Paul Chaikin and Prof. William Russel, Princeton University, obtained results that upset the current understanding of phase transitions and surprised the condensed matter physics community. Colloidal suspensions of nearly perfect hard spheres allowed to crystallize in microgravity show large crystals with dendritic arms previously undetected and unpresumed from ground-based studies. In space, they also observed crystallization of "glass" colloidal samples that fail to crystallize after more than 1 year in Earth's gravity. They also found that in space the crystals grow purely via random stacking of hexagonal planes, lacking any of the face-centered cubic components evident in the crystals grown on Earth. These observations run counter to current understanding of the fundamental aspects of phase transitions.

Also aboard USM1-2, Prof. John Hart, the University of Colorado, observed pattern formation in an experimental model of planetary atmospheres, using a device that, in a microgravity environment, simulates planetary-scale forces, including radial gravity. He obtained both qualitative and quantitative information on pattern selection and turbulent transitions that will guide future models of geophysical flow. On the same mission, Prof. Simon Ostrach, Case Western Reserve University, found and characterized a type of fluid motion, driven by the thermodynamic properties of gas-liquid interfaces, that plays an important role in materials processing in space and on Earth. These experiments have provided the scientific community with the first conclusive evidence of transition from steady to oscillatory flows, a transition that can have major consequences for crystal growth and other processing technologies.

NASA and the National Eye Institute of the NIH signed an interagency agreement to conduct further research in detecting eye diseases at their earliest stages using a compact, dynamic light scattering probe developed at NASA's LeRC. The probe was developed for conducting fluid physics experiments in challenging conditions of a microgravity environment on board a space shuttle orbiter or space station. The easy-to-use probe requires neither sensitive optical alignment, nor the use of vibration isolation devices. In a clinical setting, the probe is simply mounted on an Hruby lens holder on a regular slit-lamp apparatus available in every ophthalmologist's or optometrist's office. The NASA-NIH agreement will use the unique talents and experience of both agencies to explore the use of the probe for early detection and diagnosis of eye diseases such as cataracts, diabetic retinopathy, and the inflammatory diseases of the anterior chamber of the eye. The agreement will allow characterization of the instrument, aiding in its eventual commercial acceptance and Food and Drug Administration (FDA) approval, and

ensuring its eventual availability to the biomedical community.

Prof. Alice Gast, Stanford University, reported the development of Spatially Resolved Diffusing Wave Spectroscopy, a novel technique that allows accurate measurements of optical and dynamic properties of ordered colloidal suspensions. The high opacity of these colloids usually renders the previously existing scattering techniques unsuitable.

Prof. Van Carey, the University of California, Berkeley, used the NASA DC-9 aircraft to conduct reduced-gravity experiments to demonstrate that the use of binary fluid mixtures, rather than pure fluids, can produce significant enhancements (a factor of 3 increase for water using water/2-propanol mixture) in critical heat flux in boiling. These results could lead the way to significant improvements in the performance of power generation and thermal control for space- and Earth-based systems.

Meetings, Awards, and Publications

The Third Microgravity Fluid Physics Conference, held in Cleveland, OH on June 13-15, 1996, was attended by 385 scientists and engineers from around the world. It was a very successful meeting with 135 presentations, including three keynote addresses. Most of the papers presented were included in the conference proceedings (NASA Conference Publication 3338, 1996). In addition, the results of the work sponsored by the Program were presented at many national and international conferences, including the American Physical Society Fluid Dynamics Meeting, the 31st National Heat Transfer Conference, the Second European Symposium on Fluids in Space, the American Society of Mechanical Engineers (ASME) International Mechanical Engineering Congress and Exposition, the AIAA Aerospace Sciences Meeting and Exhibit, and the American Institute of Chemical Engineers (AIChE) Annual Meeting.

Prof. S. George Bankoff, fluid physics PI and a member of the Microgravity Fluid Physics Discipline Working Group, was awarded the 1995 Donald Q. Kern award by the AIChE in recognition of his outstanding career contributions in the field of heat transfer, especially in the areas of boiling and two-phase flow, and his ongoing contributions to those practicing the science of heat transfer and educating future heat transfer engineers. Prof. Bankoff was also elected a member of the National Academy of Engineering in 1996.

Fluid physics PI Prof. Bruce Ackerson, Oklahoma State University, won the 1996 *Journal of Rheology* publication award with Mr. Liang Chen, Helene Curtis, Inc., in Chicago, and Mr. Charles Zukoski, the University of Illinois, Urbana-Champaign. They were cited for their paper "Rheological Consequences of Microstructural Transitions in Colloidal Crystals," published in the journal in 1994.

Several U.S. microgravity researchers made presentations at the Second European Symposium on Fluids in Space held in Naples, Italy, April 22-26, 1996. Dr. Simon Ostrach, Case Western Reserve University, gave the plenary lecture on oscillatory thermocapillary flows and included results of his Surface Tension Driven Convection Experiment, which flew on USM1-2. Dr. R.S. Subramanian, Clarkson University, spoke on thermocapillary migration of bubbles and drops, a subject that he explored further with an experiment aboard the LMS mission flown in June/July 1996.

The International School on Nonlinear Problems of Hydrodynamic Stability Theory was held in Moscow, Russia, February 18-25, 1996. Most of the attendees were Russian researchers, providing NASA the opportunity to gain a better understanding of the scope of current fluid physics activities in that country.

Flight Experiments

Fluid physics experiments were conducted on the USMP-3 mission, in Getaway Special (GAS) Cans on two shuttle flights—on the LMS mission and during NASA-*Mir* joint missions *Mir*-3, -4, and -5. Scientists are still in the process of analyzing the results of these experiments.

Two successful GAS Can flights (STS-72 and STS-77) of the Pool Boiling Experiment completed the five-flight experiment program of Prof. Herman Merte, University of Michigan. The objectives of the Pool Boiling experiments were to improve understanding of the fundamental mechanisms of pool boiling by conducting tests in microgravity; the low-gravity environment removes the buoyancy effects that mask other phenomena in Earth's gravity.

Two U.S. experiments were conducted in ESA's Bubble, Drop, and Particle Unit on the 17-day LMS mission in June/July 1996. The objective of the first experiment, Thermocapillary Migration and Interactions of Bubbles and Drops, was designed to study the motion of bubble and drops in a liquid under the action of temperature gradient. Temperature gradients cause variation in the interfacial tension at the surface of the bubble or drop which propel it in the direction of the warmer liquid. The objective of the second experiment, Studies in Electrohydrodynamics, was designed to study the stability characteristics of cylindrical liquid columns under the influence of varying electric fields. This experiment focused on the series of shape changes that occur in a liquid bridge suspended between two electrodes. Both experiments were conducted successfully and the vast amounts of data generated are now being analyzed by the respective scientific teams.

The first flight of the Mechanics of Granular Materials experiment was completed on the *Mir*-4 mission (September 1996). The science objectives of the PI were to obtain quantitative knowledge of

the behavior of bulky granular materials under low confining pressures. The resultant data will be important in the understanding of soil mechanics and geotechnical engineering, earthquake engineering, coastal and off-shore engineering, mining engineering, planetary geology, granular flow processes, and engineering with granular materials. A second flight is scheduled for STS-86 in 1997 to complete the experiment data requirements matrix.

The Interface Configuration Experiment was conducted in May 1996 aboard the *Mir* space station in the MGBX facility by crew member Dr. Shannon Lucid. The experiment was developed to explore certain aspects of liquid/vapor interface behavior, primarily the uniqueness of certain mathematical predictions of fluid configurations in the absence of gravity. A brief audio report included confirmation of video recordings and completion of experiment operations. The science team retrieved the data tapes when Dr. Lucid returned to Earth in September 1996.

The Technological Evaluation of the Microgravity Isolation Mount experiment, known as the TEM, was launched to the *Mir* space station on the Priroda module in April 1996. Dr. Lucid conducted the technology demonstration in four sessions during mid-July. The TEM interfaced with the MGBX, the *Mir* Interface to Payload System (MIPS), the SAMS, and the MIM in order to assess the performance of the Canadian-built MIM. The second Technological Evaluation of the MIM (TEM-2) and the Binary Colloidal Alloy Test (BCAT) MGBX investigation were launched to the *Mir* on the *Mir*-4 mission. The objective of TEM-2 was to demonstrate the ability of the MIM to eliminate the effects of g-jitter on fluid free surface oscillations in low gravity and obtain new data on the free surface response of fluids to controlled g-jitter. The objective of BCAT was to conduct fundamental studies of the formation of colloidal superlattices and large scale

fractal colloidal aggregates/gels using long-duration exposure to microgravity, which is not available in space shuttle missions.

The FY 1996 ground and flight tasks for fluid physics are listed in table 4. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1996*, NASA Technical Memorandum 4780, March 1997.

TABLE 4.—*Fluid physics tasks funded by MSAD in FY 1996 (includes no-cost extensions).*

Flight Experiments	<i>An Experimental Study of Richtmyer-Meshkov Instability in Low Gravity</i>	<i>Behavior of Rapidly Sheared Bubbly Suspensions</i>
<i>Surface Controlled Phenomena</i> Prof. Robert E. Apfel Yale University New Haven, CT	Dr. Jeffrey W. Jacobs University of Arizona Tucson, AZ	Prof. Ashok S. Sangani Syracuse University Syracuse, NY
<i>Two-Phase Gas-Liquid Flows in Microgravity: Experimental and Theoretical Investigation of the Annular Flow</i> Prof. Vemuri Balakotaiah University of Houston Houston, TX	<i>Microgravity Segregation in Binary Mixtures of Inelastic Spheres Driven by Velocity Fluctuation Gradients</i> Prof. James T. Jenkins Cornell University Ithaca, NY	<i>Studies in Electrohydrodynamics</i> Dr. Dudley A. Saville Princeton University Princeton, NJ
<i>The Dynamics of Disorder-Order Transitions in Hard Sphere Colloidal Dispersions</i> Prof. Paul M. Chaikin Princeton University Princeton, NJ	<i>Bubble Dynamics on a Heated Surface</i> Dr. Mohammad Kassemi NASA LeRC Cleveland, OH	<i>Mechanics of Granular Materials</i> Dr. Stein Sture University of Colorado, Boulder Boulder, CO
<i>Investigations of Mechanisms Associated With Nucleate Boiling Under Microgravity Conditions</i> Dr. Vijay K. Dhir University of California, Los Angeles Los Angeles, CA	<i>Magnetorheological Fluids: Rheology and Nonequilibrium Pattern Formation</i> Prof. Jing Liu California State University, Long Beach Long Beach, CA	<i>Thermocapillary Migration and Interactions of Bubbles and Drops</i> Prof. R.S. Subramanian Clarkson University Potsdam, NY
<i>The Melting of Aqueous Foams</i> Prof. Douglas J. Durian University of California, Los Angeles Los Angeles, CA	<i>Extensional Rheology Experiment</i> Prof. Gareth H. McKinley Harvard University Cambridge, MA	<i>Drop Dynamics Investigation</i> Prof. Taylor G. Wang Vanderbilt University Nashville, TN
<i>Microscale Hydrodynamics Near Moving Contact Lines</i> Prof. Stephen Garoff Carnegie Mellon University Pittsburgh, PA	<i>Study of Two Phase Gas-Liquid Flow Behavior at Reduced Gravity Conditions</i> Dr. John McQuillen NASA LeRC Cleveland, OH	<i>A Study of the Constrained Vapor Bubble Heat Exchanger</i> Prof. Peter C. Wayner, Jr. Rensselaer Polytechnic Institute Troy, NY
<i>Geophysical Fluid Flow Cell</i> Dr. John E. Hart University of Colorado, Boulder Boulder, CO	<i>Pool Boiling Experiment</i> Prof. Herman Merte, Jr. University of Michigan Ann Arbor, MI	<i>Physics of Colloids in Space</i> Prof. David A. Weitz University of Pennsylvania Philadelphia, PA
<i>Growth and Morphology of Phase Separating Supercritical Fluids</i> Dr. John Hegseth University of New Orleans New Orleans, LA	<i>Surface Tension-Driven Convection Experiment (STDCE-1, STDCE-2)</i> Prof. Simon Ostrach Case Western Reserve University Cleveland, OH	Ground-Based Experiments <i>Experimental and Analytical Study of Two-Phase Flow Parameters in Microgravity</i> Dr. Davood Abdollahian S. Levy, Inc. Campbell, CA

Study of Nonaxisymmetric Liquid Bridges

Prof. J. Iwan D. Alexander
University of Alabama, Huntsville
Huntsville, AL

***Stability Limits and Dynamics
of Nonaxisymmetric Liquid Bridges***

Prof. J. Iwan D. Alexander
University of Alabama, Huntsville
Huntsville, AL

***Numerical Simulation of Electrochemical
Transport Processes in Microgravity
Environments***

Prof. Sanjoy Banerjee
University of California, Santa Barbara
Santa Barbara, CA

***Control of Flowing Liquid Films
by Electrostatic Fields in Space***

Prof. S. G. Bankoff
Northwestern University
Evanston, IL

Forced Oscillation of Pendant and Sessile Drops

Dr. Osman A. Basaran
Purdue University
West Lafayette, IN

Dynamics of Granular Materials

Prof. Robert P. Behringer
Duke University
Durham, NC

***Investigation of Drop Formation
by a Vortex Ring in Microgravity***

Prof. Luis P. Bernal
University of Michigan
Ann Arbor, MI

Dynamic Modeling of the Microgravity Flow

Dr. Jeremiah U. Brackbill
Los Alamos National Laboratory
Los Alamos, NM

***Marangoni Instability Induced Convection
in Evaporating Liquid Droplets***

Dr. An-Ti Chai
NASA LeRC
Cleveland, OH

***Structure, Hydrodynamics, and Phase
Transitions of Freely Suspended Liquid Crystals***

Prof. Noel A. Clark
University of Colorado, Boulder
Boulder, CO

***Fluid Interface Behavior Under Low-
and Zero-Gravity Conditions***

Prof. Paul Concus
University of California, Berkeley
Berkeley, CA

***Interface Morphology During Crystal Growth:
Effects of Anisotropy and Fluid Flow***

Dr. Sam R. Coriell
National Institute of Standards and Technology
Gaithersburg, MD

***Phoretic and Radiometric Force Measurements
on Microparticles Under Microgravity
Conditions***

Dr. E.J. Davis
University of Washington
Seattle, WA

***Cell and Particle Interactions and Aggregation
During Electrophoretic Motion***

Prof. Robert H. Davis
University of Colorado, Boulder
Boulder, CO

Theory of Solidification

Prof. Stephen H. Davis
Northwestern University
Evanston, IL

Microgravity Foam Structure and Rheology

Prof. Douglas J. Durian
University of California, Los Angeles
Los Angeles, CA

***Magnetothermal Convection in Nonconducting
Diamagnetic and Paramagnetic Fluids***

Prof. Boyd F. Edwards
West Virginia University
Morgantown, WV

***Effects of Gravity on Sheared Turbulence
Laden With Bubbles or Droplets***

Prof. Said E. Elghobashi
University of California, Irvine
Irvine, CA

***Evaporation, Boiling, and Condensation
on/in Capillary Structures of High Heat Flux
Two-Phase Devices***

Prof. Amir Faghri
University of Connecticut
Storrs, CT

***The Influence of Gravity on Nucleation,
Growth, Stability and Structure in Ordering
Soft-Spheres***

Prof. Alice P. Gast
Stanford University
Stanford, CA

Material Instabilities in Particulate Systems

Dr. Joe D. Goddard
University of California, San Diego
La Jolla, CA

***Thermoacoustic Effects at a Solid-Fluid
Boundary: The Role of a Second-Order
Thermal Expansion Coefficient***

Dr. Ashok Gopinath
Naval Postgraduate School
Monterey, CA

Capillary-Elastic Instabilities in Microgravity

Prof. James B. Grotberg
Northwestern University
Evanston, IL

***Instability Mechanisms in Thermally-Driven
Interfacial Flows in Liquid-Encapsulated
Crystal Growth***

Prof. Hossein Haj-Hariri
University of Virginia
Charlottesville, VA

***A Study of the Microscale Fluid Physics
in the Near Contact Line Region
of an Evaporating Capillary Meniscus***

Prof. Kevin P. Hallinan
University of Dayton
Dayton, OH

***A Geophysical Flow Experiment
in a Compressible Critical Fluid***

Dr. John Hegseth
University of New Orleans
New Orleans, LA

Experimental Investigation of Pool Boiling Heat Transfer Enhancement in Microgravity in the Presence of Electric Fields

Dr. Cila Herman
Johns Hopkins University
Baltimore, MD

Problems in Microgravity Fluid Mechanics: Thermocapillary Instabilities and G-jitter Convection

Prof. George M. Homsy
Stanford University
Stanford, CA

Surfactant-Based Critical Phenomena in Microgravity

Prof. Eric W. Kaler
University of Delaware
Newark, DE

Bubble Generation in a Flowing Liquid Medium and Resulting Two-Phase Flow in Microgravity

Dr. Yasuhiro Kamotani
Case Western Reserve University
Cleveland, OH

Studies in Thermocapillary Convection of the Marangoni-Bénard Type

Prof. Robert E. Kelly
University of California, Los Angeles
Los Angeles, CA

Two-Phase Annular Flow in Helical Coil Flow Channels in a Reduced Gravity Environment

Prof. Edward G. Keshock
Cleveland State University
Cleveland, OH

Investigation of Pool Boiling Heat Transfer Mechanisms in Microgravity Using an Array of Surface Mounted Heat Flux Sensors

Prof. Jungho Kim
University of Denver
Denver, CO

Molecular Dynamics of Fluid-Solid Systems

Prof. Joel Koplik
City College of New York
New York, NY

Thermocapillary Convection in Low Pr Materials Under Simulated Reduced-Gravity Conditions

Prof. Sindo Kou
University of Wisconsin
Madison, WI

Electric Field Induced Interfacial Instabilities

Dr. Robert E. Kusner
NASA LeRC
Cleveland, OH

The Breakup and Coalescence of Gas Bubbles Driven by the Velocity Gradients of a Non-Uniform Flow

Dr. L.G. Leal
University of California, Santa Barbara
Santa Barbara, CA

The Micromechanics of the Moving Contact Line

Prof. Seth Lichter
Northwestern University
Evanston, IL

Absolute and Convective Instability of a Liquid Jet at Microgravity

Prof. Sung P. Lin
Clarkson University
Potsdam, NY

Rheology of Concentrated Emulsions

Prof. Michael Loewenberg
Yale University
New Haven, CT

Investigation of Thermal Stress Convection in Nonisothermal Gases

Under Microgravity Conditions

Dr. Daniel W. Mackowski
Auburn University
Auburn, AL

The Dissolution of an Interface Between Miscible Liquids

Prof. James V. Maher
University of Pittsburgh
Pittsburgh, PA

Passive or Active Radiation Stress Stabilization of (and Coupling to) Liquid Bridges and Bridge Networks

Prof. Philip L. Marston
Washington State University
Pullman, WA

Fundamental Processes of Atomization in Fluid-Fluid Flows

Prof. Mark J. McCready
University of Notre Dame
Notre Dame, IN

A Study of Nucleate Boiling With Forced Convection in Microgravity

Prof. Herman Merte, Jr.
University of Michigan
Ann Arbor, MI

Determination of Interfacial Rheological Properties Through Microgravity Oscillations of Bubbles and Drops

Dr. Ali Nadim
Boston University
Boston, MA

NMRI Measurements and Granular Dynamics Simulations of Segregation of Granular Mixtures

Prof. Masami Nakagawa
The Lovelace Institutes
Golden, CO

Non-Coalescence Effects in Microgravity

Prof. G.P. Neitzel
Georgia Institute of Technology
Atlanta, GA

Production of Gas Bubbles in Reduced Gravity Environments

Dr. Hasan N. Oguz
Johns Hopkins University
Baltimore, MD

Waves in Radial Gravity Using Magnetic Fluid

Dr. Daniel R. Ohlsen
University of Colorado
Boulder, CO

Industrial Processes Influenced by Gravity

Prof. Simon Ostrach
Case Western Reserve University
Cleveland, OH

On the Boundary Conditions at an Oscillating Contact Line: A Physical/Numerical Experimental Program

Dr. Marc Perlin
University of Michigan
Ann Arbor, MI

Fluid Dynamics and Solidification of Molten Solder Droplets Impacting on a Substrate in Microgravity

Dr. Dimos Poulikakos
University of Illinois at Chicago
Chicago, IL

Acoustic Bubble Removal from Boiling Surfaces

Prof. Andrea Prosperetti
Johns Hopkins University
Baltimore, MD

Containerless Ripple Turbulence

Dr. Seth J. Putterman
University of California, Los Angeles
Los Angeles, CA

Decoupling the Role of Inertia and Gravity on Particle Dispersion

Dr. Chris B. Rogers
Tufts University
Medford, MA

Design/Interpretation of Microgravity Experiments to Obtain Fluid/Solid Boundary Conditions in Non-Isothermal Systems

Prof. Daniel E. Rosner
Yale University
New Haven, CT

Ground Based Studies of Internal Flows in Levitated Laser-Heated Drops

Prof. Satwindar S. Sadhal
University of Southern California
Los Angeles, CA

Terrestrial Experiments on G-Jitter Effects on Transport and Pattern Formation

Dr. Michael F. Schatz
Georgia Institute of Technology
Atlanta, GA

Free-Surface and Contact-Line Motion of Liquids in a Microgravity Environment

Dr. Leonard W. Schwartz
University of Delaware
Newark, DE

Drop Breakup in Flow Through Fixed Beds as Model Stochastic Strong Flows

Dr. Eric S. Shaqfeh
Stanford University
Stanford, CA

Transport Processes Research

Dr. Bhim S. Singh
NASA LeRC
Cleveland, OH

Solute Nucleation and Growth in Supercritical Fluid Mixtures

Dr. Gregory T. Smedley
California Institute of Technology
Pasadena, CA

The Development of Novel, High-Flux, Heat Transfer Cells for Thermal Control in Microgravity

Prof. Marc K. Smith
Georgia Institute of Technology
Atlanta, GA

Dynamics of the Molten Contact Line

Dr. Ain A. Sonin
Massachusetts Institute of Technology
Cambridge, MA

Marangoni Effects on Drop Deformation and Break-Up in an Extensional Flow: The Role of Surfactant Physical Chemistry

Dr. Kathleen J. Stebe
Johns Hopkins University
Baltimore, MD

Stability of Shapes Held by Surface Tension and Subjected to Flow

Prof. Paul H. Steen
Cornell University
Ithaca, NY

Instabilities in Surface-Tension-Driven Convection

Prof. Harry L. Swinney
University of Texas at Austin
Austin, TX

Crystal Growth and Fluid Mechanics Problems in Directional Solidification

Prof. Saleh Tanveer
Ohio State University
Columbus, OH

Microgravity Effects on Transendothelial Transport

Dr. John M. Tarbell
Pennsylvania State University
University Park, PA

Studies of Particle Sedimentation by Novel Scattering Techniques

Prof. Penger Tong
Oklahoma State University
Stillwater, OK

Acoustic Streaming in Microgravity: Flow Stability and Heat Transfer Enhancement

Dr. Eugene H. Trinh
NASA JPL
Pasadena, CA

Fluid Physics in a Stochastic Acceleration Environment

Prof. Jorge Viñals
Florida State University
Tallahassee, FL

Fundamental Physics

Overview

The goal of the fundamental physics program is to use the microgravity environment of space to shed light on the most fundamental physical laws that govern the behavior of matter. An understanding of these laws, and the advanced technology developed in order to study these laws with unprecedented precision, are used in applications that support and enhance the human presence in space, improve the quality of life on Earth, and contribute to the competitiveness of American industry. One example is completed and planned high-resolution tests of the Renormalization Group (RG) theory. The RG theory constitutes one of the greatest achievements of theoretical physics of the past 30 years. The increased understanding of the validity of use of the RG theory to such disciplines as percolation, pattern formation, and evolution of turbulence, will help scientists develop better models for how water seeps through soil, how frost heaving occurs in arctic climates, and how turbulent weather systems evolve.

Examples of uses of the advanced technologies being developed in the program are: superconducting magnetometers for efficient resource mining and noninvasive medical diagnostics; management of cryogenic fluids for life support systems and manufacturing use; and use of highly accurate low-temperature clocks for navigation, global positioning, and communications.

The fundamental physics program saw significant growth in FY 1996, as 25 new investigators were selected for multiyear funding from the 1994 fluids NRA. Two of the selections were for flight definition studies requiring the extended lifetime of the planned Low Temperature Microgravity Physics (LTMP) facility for the *ISS* to accomplish their science objectives. Four of the fundamental physics selections were in

the relatively new area of laser cooling of atoms; the use of microgravity in this field promises to significantly enhance uncovering scientific principles masked by gravity. The advanced technology that will result from these gains in our basic understanding of atoms, such as high-stability clocks, will enhance the ability of humans to live and work in space and contributes to improving the quality of life on Earth. The Confined Helium Experiment (CHeX) flight experiment, which studies fundamental questions regarding the influence of boundaries on the behavior of matter, started system integration and testing at JPL in January 1996. CHeX will be launched on the space shuttle as part of USMP-4, currently planned for November 1997. Another planned shuttle experiment, the Critical Dynamics in Microgravity Experiment (DYNAMX), conducted its Science Concept Review in January 1996. This experiment will reuse most of the CHeX flight hardware to study fundamental principles of nature under dynamic conditions that occur near transitions from one state of matter to another.

The selection of 23 ground-based investigations for the fundamental physics program from the 1994 fluids NRA represented a 50-percent increase in the number of ground-based research tasks supported in this program, and has introduced new areas of research into the discipline. The addition of four investigations of laser-cooled atoms into the fundamental physics program adds many very basic topics to be studied, such as phenomena occurring in Bose-Einstein condensates and tests of the Standard Model of physics using precise measurements made possible by the very cold temperatures (within 10^{-9} degree of absolute zero) of the atomic sample. The growing community of investigators and the maturity of their investigations has led

to increases in the number of publications produced, and should also lead to a larger number of proposals for flight experiments in the next NRA for this discipline.

Achievements during FY 1996 from the ground-based investigations include:

- Investigators at JPL have developed a superconducting magnet technique that allows up to a 100 times reduction in the impacts of gravity on fluid samples. This technique can be used to simulate the gravity environment of both the Moon and Mars in most types of fluid systems. Small-scale cryogenic fluid management systems can be developed and tested under realistic conditions with this technique to help optimize designs for use in lunar or Mars colonies.
- Produced 17 presentations, 43 proceedings papers, and 12 articles in refereed journals, plus a chapter in a book.
- Supported 33 students working toward their doctoral degrees and 6 undergraduate students. Three of the doctoral candidates obtained their degrees during FY 1996, as did one undergraduate.
- The results of the Lambda Point Experiment were published in the premier journal of the physics community, *Physical Review Letters* (76, 944 (1996)). The JPL Fundamental Physics Steering Group, consisting mostly of scientists in the ground-based research program, prepared a document describing 11 significant accomplishments that the flight experiment achieved.
- The Fundamental Physics Steering Group, with advice and assistance

from other scientists in the ground-based and flight programs, prepared a draft science plan for the fundamental physics in microgravity discipline, including the subject areas of low-temperature physics, condensed matter physics, laser cooling atomic physics, and gravitation and relativity physics.

Meetings, Awards, and Publications

The 1996 NASA/JPL Low-Temperature Microgravity Physics Workshop attracted 82 attendees to Pasadena, CA, to present and hear descriptions of ideas for research in microgravity. Scientists described research topics in critical point statics and dynamics in liquid helium (He) at the ^3He gas-liquid critical point and in ^3He - ^4He mixtures near the tricritical point; topics in laser-cooled atoms that included precise measurements of the electric dipole moment of the electron to test the Standard Model, studies of Bose-Einstein condensed atoms, and laser-cooled atoms for clock applications; and relativity and gravitation experiments to test assumptions of the Theory of General Relativity, such as the Equivalence Principle. Discussions of subjects appropriate to the Science Plan for this discipline elicited several new topics to be included, but also illustrated the common ground that these science areas share. A proceedings document (NASA D-13845, 1996) was published with summaries of the workshop presentations.

The 15th International Atomic Physics Conference took place August 5–9, 1996, in Amsterdam, the Netherlands. Dr. Don Strayer, JPL, represented the microgravity fundamental physics program at the conference.

The 21st International Conference on Low-Temperature Physics was held in Prague, the Czech Republic, August 8–14, 1996. The conference drew approximately 1,500 participants from around the world, including a majority of the Microgravity Science Research Program-sponsored investigators in fundamental physics, who

presented papers. Dr. Ulf Israelsson, lead scientist for fundamental physics at JPL, gave an invited paper on the potential of low-temperature research on the *ISS*.

The 1996 Nobel Prize for physics was awarded to Dr. David M. Lee (Cornell University), Dr. Douglas D. Osheroff (Stanford University), and Dr. Robert C. Richardson (Cornell University). The prize was awarded for their discovery of the superfluidity of ^3He at a temperature of approximately two-thousandths of a degree above absolute zero. Dr. Lee has agreed to serve on the 1994 NRA low-temperature physics review panel, and will be asked to serve on the 1996 NRA panel as well. Dr. Richardson served on the science review panel for Gravity Probe B (NASA's Relativity Mission).

Flight Experiments

The CHEx will take data very near the superfluid phase transition in liquid helium, investigating helium confined between close-spaced silicon wafers. These data will be used to test theories of finite-size effects when a system is constrained to two dimensions. The data will be taken at resolutions and length scales not achievable on Earth. To achieve its science goals, this experiment will take advantage of the microgravity environment of space, of the unique properties of helium, and of superconducting high-resolution thermometry. The scientific results from CHEx will have important applications in understanding the behavior of thin samples of materials used, for example, in the semiconductor industry. The CHEx PI is Prof. John Lipa, Stanford University. Achievements during FY 1996 include:

- Completed instrument assembly and test
- Completed instrument/cryostat integration
- Demonstrated remote operations at the PI's home facility (Stanford University)
- Completed all system environmental tests.

The CHEx will complete the environmental testing phase early in 1997 and will then prepare to ship to Kennedy Space Center (KSC) for integration with the space shuttle.

A Science Concept Review (SCR) for the DYNAMX experiment was conducted in January 1996. The DYNAMX PI is Prof. Robert Duncan, the University of New Mexico. DYNAMX has been preparing for the Requirements Definition Review during the latter part of FY 1996. The DYNAMX team's achievements during FY 1996 include:

- Prepared for and passed the Science Concept Review, obtaining the review panel's recommendation for continuing to the Requirements Definition Review sometime in FY 1997. Several concerns raised by the Science Concept Review panel were addressed by the DYNAMX team during FY 1996.
- Developed high-resolution thermometers and installed them in a new cryostat probe at the University of New Mexico for the ground-based measurements. This cryoprobe has a novel caged cell that limits the amount of stray heat going in or coming out of the cell.
- Fabricated two cells for ground-based measurements—one for a heat-from-above test, the other for a heat-from-below test. The data taken at the University of New Mexico with the heat-from-above cell demonstrated for the first time in liquid helium the phenomenon of self-organizing criticality. This new result has been accepted for publication in *Physical Review Letters*.
- Developed designs for the flight instrument hardware, including structural elements for the flight experimental cell, and a vibration isolation system for the instrument. Fabricated a prototype cell and tested it to launch vibration levels.

- Analyzed the heating that will occur from ionizing radiation during the flight experiment and devised a design for smaller high-resolution thermometers to alleviate heating effects of the radiation on data.
- Studied the ability of a heat current to stabilize the interface between the superfluid and the normal fluid in microgravity. On Earth, gravity stabilizes the position of this interface. The results on self-organizing critical behavior demonstrate that, in the absence of gravity effects, the heat current can also stabilize the interface. Analysis work by collaborators at California Institute of Technology also indicates the conditions for stabilization of the interface. DYNAMX will study this interface in space under conditions that cannot be obtained on Earth.

The Satellite Test of the Equivalence Principle (STEP) experiment has the objective of testing the scientific principle underpinning the Theory of General Relativity—the principle of the equivalence of inertial mass and gravitational mass. STEP has been downscaled to become MiniSTEP, a smaller, less expensive flight mission. Agreements for cooperation are being negotiated with representatives of the ESA and with national space agencies. During FY 1996, several accomplishments were realized in the development of the instrument technology:

- Minor improvements have been made in the flux microscope that will be used to examine the uniformity of magnetic flux in the magnetic bearings of the differential accelerometers.
- The Superconducting Quantum Interference Device (SQUID) position sensor test-bed has undergone its third major revision, applying quartz flats to support the niobium thin-film pick-up coils. Commercial SQUID devices are now being used with electronics developed for the Gravity Probe B experiment.

- The system for photolithography on cylinders has been improved so that now the deposition of thin film patterns of niobium is reproducible to better than a micron.
- The system for electrostatic positioning of the levitated masses is now capable of making position measurements in 6 degrees of freedom. The sensitivity was shown to achieve sub-micrometer resolution. A new test-bed is being developed to demonstrate sensitivity at the nanometer level.
- The major components of a tipper table have been assembled. This table will be used to develop control laws for the levitated masses of the differential accelerometers.
- A vacuum probe has been constructed to test components at liquid helium temperatures by dipping them into a liquid helium storage Dewar, and has been used to measure the motions of flux with a direct current SQUID. Similar probes will be assembled for studying other superconducting components that are needed to operate the differential accelerometers.

The Superfluid Universality Experiment (SUE) was chosen in February 1996 to be a flight definition experiment for operation on the *ISS*. SUE will measure properties of superfluid helium just below the phase transition to determine critical parameters at the transition. These measurements will be repeated at several pressures to test the universality predictions of theories of such transitions. Performing the experiment in space will accelerate discoveries, allowing measurements much closer to the transition temperature to greatly improve testing of the theories. The PI for SUE is Prof. John Lipa, Stanford University. In FY 1996, Prof. Lipa participated on the science planning team for the *ISS* LTMP facility.

The Microgravity Investigation of Scaling Theory Experiment was also chosen for flight definition for operation on the *ISS* from the 1994 fluids NRA. The PI is Dr. Martin Barmatz, NASA JPL. This experiment will measure three parameters near the gas-liquid critical point in ^3He , thus allowing tests of theories for the scaling and hyperscaling relationships between these parameters. This experiment will provide all three parameters measured from one sample in one series of measurements so, for the first time, these relations can be tested without the uncertainties of calibration and sample differences that have plagued earlier comparisons of critical scaling. Performing the measurements in microgravity will permit these critical parameters to be measured very close to the phase transition where the anomalous critical point behavior is clearly dominant, so corrections to the theory caused by noncritical behavior will be negligible and the tests will be more characteristic of the predictions of critical point theories. During FY 1996, Dr. Barmatz participated in the planning of the *ISS* LTMP facility by serving on the science planning committee.

The Critical Fluid Light Scattering Experiment/Zeno successfully completed its second flight on the USMP-3 mission. This experiment extends and improves measurements of the decay rates and the correlation length of critical fluctuations in a simple fluid very near its liquid-vapor critical point. This second flight completes the flight-experiment program of PI Dr. Robert Gammon, University of Maryland. The flight data are now being analyzed.

The FY 1996 ground and flight tasks for fundamental physics are listed in table 5. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1996*, NASA Technical Memorandum 4780, March 1997.

TABLE 5.—*Fundamental physics tasks funded by MSAD in FY 1996 (includes no-cost extensions).*

Flight Experiments

Microgravity Test of Universality and Scaling Predictions Near the Liquid-Gas Critical Point of ^4He

Dr. Martin B. Barmatz
NASA JPL
Pasadena, CA

Critical Viscosity of Xenon

Dr. Robert F. Berg
National Institute of Standards and Technology
Gaithersburg, MD

Critical Dynamics in Microgravity

Prof. Robert V. Duncan
University of New Mexico
Albuquerque, NM

Satellite Test of the Equivalence Principle (STEP)

Prof. C.W.F. Everitt
Stanford University
Stanford, CA

Critical Fluid Light Scattering Experiment—Zeno

Prof. Robert W. Gammon
University of Maryland
College Park, MD

Confined Helium Experiment (CHeX)

Prof. John A. Lipa
Stanford University
Stanford, CA

A New Test of Critical-Point Universality by Measuring the Superfluid Density Near the Lambda Line of Helium

Prof. John A. Lipa
Stanford University
Stanford, CA

Ground-Based Experiments

Superfluid Transition of ^4He in the Presence of a Heat Current

Prof. Guenter Ahlers
University of California, Santa Barbara
Santa Barbara, CA

The Superfluid Transition of ^4He Under Unusual Conditions

Prof. Guenter Ahlers
University of California, Santa Barbara
Santa Barbara, CA

Microgravity Test of Universality and Scaling Predictions Near the Liquid-Gas Critical Point of ^3He

Dr. Martin B. Barmatz
NASA JPL
Pasadena, CA

New Phenomena in Strongly Counterflowing He-II Near T_l

Dr. Stephen T. Boyd
University of New Mexico
Albuquerque, NM

Prediction of Macroscopic Properties of Liquid Helium From Computer Simulation

Prof. David M. Ceperley
University of Illinois, Urbana-Champaign
Urbana, IL

Measurement of the Heat Capacity of Superfluid Helium in a Persistent-Current State

Dr. Talso C. Chui
NASA JPL
Pasadena, CA

Nonequilibrium Phenomena Near the Lambda Transition of ^4He

Dr. Talso C. Chui
NASA JPL
Pasadena, CA

The Lambda Transition Under Superfluid Flow Conditions

Dr. Talso C. Chui
NASA JPL
Pasadena, CA

Nucleation of Quantized Vortices From Rotating Superfluid Drops

Prof. Russell J. Donnelly
University of Oregon
Eugene, OR

Kinetic and Thermodynamic Studies of Melting-Freezing of Helium in Microgravity

Prof. Charles Elbaum
Brown University
Providence, RI

Critical Dynamics of Ambient Temperature and Low Temperature Phase Transitions

Prof. Richard A. Ferrell
University of Maryland, College Park
College Park, MD

Dynamics of Superfluid Helium in Low Gravity

Mr. David J. Frank
Lockheed Martin Missiles & Space Co.
Palo Alto, CA

Investigation of Future Microgravity Atomic Clocks

Prof. Kurt Gibble
Yale University
New Haven, CT

Condensate Fraction in Superfluid Helium Droplets

Prof. J. Woods Halley
University of Minnesota
Minneapolis, MN

Ultra-Precise Measurements With Trapped Atoms in a Microgravity Environment

Dr. Daniel J. Heinzen
University of Texas
Austin, TX

Precision Measurements With Trapped, Laser-Cooled Atoms in a Microgravity Environment

Dr. Daniel J. Heinzen
University of Texas
Austin, TX

Collisional Frequency Shifts Near Zero-Energy Resonance

Prof. Randall G. Hulet
Rice University
Houston, TX

Dynamic Measurement Near the Lambda-Point in a Low-g Simulator on the Ground

Dr. Ulf E. Israelsson
NASA JPL
Pasadena, CA

Dynamic Measurements Along the Lambda Line of Helium in a Low-Gravity Simulator on the Ground

Dr. Ulf E. Israelsson
NASA JPL
Pasadena, CA

Atom Interferometry in a Microgravity Environment

Dr. Mark A. Kasevich
Stanford University
Stanford, CA

Static Properties of ^4He in the Presence of a Heat Current in a Low-Gravity Simulator

Dr. Melora E. Larson
NASA JPL
Pasadena, CA

Second Sound Measurements Near the Tricritical Point in ^3He - ^4He Mixtures

Dr. Melora E. Larson
NASA JPL
Pasadena, CA

Effect of Confinement on Transport Properties by Making Use of Helium Near the Lambda Point

Prof. John A. Lipa
Stanford University
Stanford, CA

Red-Shift Test of General Relativity on Space Station Using Superconducting Cavity Oscillators

Prof. John A. Lipa
Stanford University
Stanford, CA

A Renewal Proposal to Study the Effect of Confinement on Transport Properties by Making Use of Helium Along the Lambda Line

Prof. John A. Lipa
Stanford University
Stanford, CA

Theoretical Studies of the Lambda Transition of Liquid ^4He

Prof. Efstratios Manousakis
Florida State University
Tallahassee, FL

Theoretical Studies of Liquid ^4He Near the Superfluid Transition

Prof. Efstratios Manousakis
Florida State University
Tallahassee, FL

Dynamics and Morphology of Superfluid Helium Drops in a Microgravity Environment

Prof. Humphrey J. Maris
Brown University
Providence, RI

Equilibration in Density and Temperature Near the Liquid-Vapor Critical Point

Prof. Horst Meyer
Duke University
Durham, NC

Density Equilibration in Fluids Near the Liquid-Vapor Critical Point

Prof. Horst Meyer
Duke University
Durham, NC

Indium Mono-Ion Oscillator II

Prof. Warren Nagourney
University of Washington
Seattle, WA

Nonlinear Relaxation and Fluctuations in a Non-Equilibrium, Near-Critical Liquid With a Temperature Gradient

Prof. Alexander Z. Patashinski
Northwestern University
Evanston, IL

Superfluid Density of Confined ^4He Near Tl

Dr. David Pearson
NASA JPL
Pasadena, CA

Finite Size Effects Near the Liquid-Gas Critical Point of ^4He

Dr. Joseph Rudnick
University of California, Los Angeles
Los Angeles, CA

Dynamics and Morphology of Superfluid Helium Drops in a Microgravity Environment

Prof. George M. Seidel
Brown University
Providence, RI

Precise Measurements of the Density and Thermal Expansion of ^4He Near the Lambda Transition

Dr. Donald M. Strayer
NASA JPL
Pasadena, CA

Precise Measurements of the Density and Critical Phenomena of Helium Near Phase Transitions

Dr. Donald M. Strayer
NASA JPL
Pasadena, CA

Materials Science

Overview

One of the goals of materials science is to study how materials form and how the forming process controls the material's properties. By careful modeling and experimentation, the mechanisms by which materials are formed can be better understood, and processing controls better designed and improved. In this way materials scientists can design new metal alloys, semiconductors, ceramics, glasses, and polymers to improve the performance of a wide range of products, from complex computers to stronger, more durable metal alloys.

The production processes for most materials includes steps that are very heavily influenced by the force of gravity. The opportunity to observe, monitor, and study these processes in low gravity promises to increase our fundamental understanding of production processes and their effects on the properties of the materials produced. Of particular interest is understanding the role of gravity driven convection in the processing of such materials. Scientists use the insights gained from low-gravity and space research to improve and control the properties of materials ranging from glass and steel to semiconductors and plastics.

The Requirements Definition Review was held in March 1996, for the completion of two materials science programs that conducted initial investigations on the LMS mission in June/July 1996, using the AGHF. The science programs are Coupled Growth in Hypermonotectics (CGH), conducted by Dr. J. Barry Andrews, the University of Alabama, Birmingham, and Particle Engulfment and Pushing Solidifying Interfaces (PEP), conducted by Dr. Doru M. Stefanescu, the University of Alabama. This peer review also covered the High Gradient Furnace With Quench hardware proposed

to conduct these projects on the *ISS*. This apparatus was recommended by the International Furnace Working Group for development as a multiuser facility for early use on the *ISS* to process metals and alloys materials. Both the CGH and PEP programs have great promise for direct application to materials used in superconductors, magnetic materials, catalysts, and electrical contacts. The objectives of CGH include demonstrating the possibility of obtaining interface stability and steady-state coupled growth in hypermonotectic alloys through microgravity processing and mapping out the limits for interface stability in hypermonotectic alloys. The objectives of PEP include improving the understanding of the physics associated with solidification of liquid metals/ceramic particles mixtures and generating accurate value for critical velocity in a convection-free environment.

The Liquid Metal Diffusion investigation was selected and approved in March 1996, as a risk mitigation opportunity for the Self-Diffusion in Liquid Elements (SDLE) project, whose PI is Dr. Franz Rosenberger. The SDLE project is currently in the definition stage and is to be developed as a flight experiment for the *ISS*. The technological goal of the project is to develop and to test the technique of measuring diffusion coefficients by in situ measurements using radioactive tracers. These in situ measurements are desirable because the measurement of multiple diffusion measurements at different temperatures should be attainable using a single sample. The SDLE scientific goals are to accurately measure diffusion coefficients of several elements at multiple temperatures to determine if there is class-like behavior in these materials and, if so, what is the correct mathematical description of that behavior.

NASA awarded 51 microgravity materials science research and analysis investigations based on peer review of over 200 proposals received as the result of an NRA released in 1994. These awards range from basic and applied scientific research to the development of advanced data acquisition and thermophysical condition-generation technology. The awardees will conduct research each year through FY 2000. Science Concept Reviews for these investigators are planned for FY 1997, with Requirements Definition Reviews planned for FY 1998.

Meetings, Awards, and Publications

MSFC hosted the Second Microgravity Materials Science Conference in Huntsville, AL, June 10–11, 1996. The meeting provided a forum for 60 PI's in the materials science discipline to make oral and poster presentations about their research to 320 conference participants. The conference goals were to: stimulate new ideas, expand the materials science community's interest in micro-gravity research, present the status of existing and planned microgravity materials science research programs, and provide information about and solicit proposals for the upcoming materials science NRA. The proceedings from this conference were published on the Internet, as well as distributed in hard copy to all conference attendees.

The 10th American Conference on Crystal Growth (ACCG-10) was held in Vail, CO, August 5–9, 1996. Sponsored in part by the NASA HQ MSAD, the conference offered the opportunity for numerous NASA materials science researchers to present their results to a diverse audience. Additionally, Dr. Stefanescu presented a paper at the

Minerals, Metals, and Materials Society's 125th Annual Meeting, February 4–8, 1996, in Anaheim, CA.

The Society of Photo-Optical Instrumentation Engineers (SPIE) sponsored its first conference on the space processing of materials at its annual International Symposium on Optical Science, Engineering, and Instrumentation, held August 4–9, 1996, in Denver, CO. SPIE hopes to hold this space processing conference annually. The 1996 conference topics included materials for detectors and electronics, and theory and applications of thin film technology. Special sessions on microgravity experiments and thin film technology were also held. Researchers from MSFC, LeRC, and JSC presented papers at the majority of sessions. Dr. Narayanan Ramachandran, from the Universities Space Research Association at MSFC, served as conference chairman and editor of the conference proceedings.

Flight Experiments

The successful processing of a mercury-cadmium-telluride sample in the Advanced Automated Directional Solidification Furnace (AADSf) hardware aboard the USMP-2 mission led to an additional opportunity for processing of a crystal growth sample in the USMP-3 mission. The AADSf hardware for USMP-3 was series hardware, which is hardware of the same or similar design to previously flown hardware.

Dr. Archibald Fripp, LaRC, conducted research on USMP-3 with an investigation entitled Compound Semiconductor Growth in a Low-g Environment, using a lead-tin-telluride (PbSnTe) sample. The coinvestigators are Mr. William Debnam

and Dr. Ivan Clark, also of LaRC. The purpose of the investigation is to determine how gravity-driven convection affects the composition of alloys where convection is driven by both thermal and compositional gradients. This is accomplished by comparing alloy semiconductors grown by the directional solidification technique on Earth and in the microgravity environment of low-Earth orbit. To determine the maximum sensitivity to microgravity forces occurring in orbital flight, the experiment sample was divided into three distinct sections in order to grow a complete crystal with the microgravity acceleration: (1) in the same direction as growth (along the length of the sample), (2) opposite the direction of growth (also along the length of the sample), and (3) perpendicular to the direction of growth (across the diameter of the sample). During the USMP-3 mission, the differences in space and ground experiments conducted in the AADSf began to manifest as the first crystal started to form. The temperature signature of the crystal nucleation in each of the three cells was much more subdued than observed in Earth-based experimentation. The analysis of the effects of microgravity growth of these crystals is proceeding at LaRC with Dr. Fripp and his team of investigators.

Dr. Andrews and Dr. Stefanescu took advantage of the "flight of opportunity" aboard LMS in June/July 1996. Each PI was able to process three samples for their respective experiments. Dr. Andrews' experiment, Coupled Growth in Hypermonotectics, studies the effects of convection during the solidifying of aligned hypermonotectic or immiscible alloys. The three samples were aluminum-indium (Al-In), with the percentage by weight of indium varying from 17.3 to

19.7 percent. The samples had the same solidification rate (1 micrometer per second). The samples were processed as planned and postflight analysis is continuing. Dr. Stefanescu's experiment, Particle Engulfment and Pushing at Solidifying Interfaces, studies the physics of solidifying liquid metals containing ceramic particles. Two of his flight samples were pure Al matrixes with 500-micrometer zirconium oxide (ZrO_2) spherical particles. The third sample was an aluminum-nickel (Al-Ni) eutectic alloy matrix with 500-micrometer ZrO_2 spherical particles. The samples were processed as planned and postflight analysis is continuing. Both PIs will utilize results from the LMS flight to further refine their processes in anticipation of more experimental opportunities aboard the ISS.

The FY 1996 ground and flight tasks for materials science are listed in table 6. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1996*, NASA Technical Memorandum 4780, March 1997.

TABLE 6.—*Materials science tasks funded by MSAD in FY 1996 (includes no-cost extensions).*

Flight Experiments

In Situ Monitoring of Crystal Growth Using MEPHISTO

Dr. Reza Abbaschian
University of Florida
Gainesville, FL

Coupled Growth in Hypermonotectics

Dr. J. Barry Andrews
University of Alabama, Birmingham
Birmingham, AL

Fundamental Aspects of Vapor Deposition and Etching Under Diffusion Controlled Transport Conditions

Dr. Klaus J. Bachmann
North Carolina State University
Raleigh, NC

Investigation of the Relationship Between Undercooling and Solidification Velocity

Dr. Robert J. Bayuzick
Vanderbilt University
Nashville, TN

Experiments on Nucleation in Different Flow Regimes

Dr. Robert J. Bayuzick
Vanderbilt University
Nashville, TN

Equiaxed Dendritic Solidification Experiment

Prof. Christoph Beckermann
University of Iowa
Iowa City, IA

Alloy Undercooling Experiments in Microgravity Environment

Dr. Merton C. Flemings
Massachusetts Institute of Technology
Cambridge, MA

Measurement of the Viscosity and Surface Tension of Undercooled Melts Under Microgravity Conditions and Supporting Magnetohydrodynamic Calculations

Dr. Merton C. Flemings
Massachusetts Institute of Technology
Cambridge, MA

Compound Semiconductor Growth in Low-g Environment

Dr. Archibald L. Fripp
NASA LaRC
Hampton, VA

Gravitational Role in Liquid-Phase Sintering

Prof. Randall M. German
Pennsylvania State University
University Park, PA

Isothermal Dendritic Growth Experiment

Prof. Martin E. Glicksman
Rensselaer Polytechnic Institute
Troy, NY

Physical Properties and Processing of Undercooled Metallic Glass Forming Liquids

Dr. William L. Johnson
California Institute of Technology
Pasadena, CA

Thermophysical Properties of Metallic Glasses and Undercooled Alloys

Dr. William L. Johnson
California Institute of Technology
Pasadena, CA

Orbital Processing of High Quality Cadmium Telluride

Prof. David J. Larson, Jr.
State University of New York, Stony Brook
Stony Brook, NY

Orbital Processing of Eutectic Rod-Like Arrays

Prof. David J. Larson, Jr.
State University of New York, Stony Brook
Stony Brook, NY

Crystal Growth of II-VI Semiconducting Alloys by Directional Solidification

Dr. Sandor L. Lehoczký
NASA MSFC
Marshall Space Flight Center, AL

Growth of Solid Solution Single Crystals

Dr. Sandor L. Lehoczký
NASA MSFC
Marshall Space Flight Center, AL

The Study of Dopant Segregation Behavior During the Growth of GaAs in Microgravity

Prof. David H. Matthiesen
Case Western Reserve University
Cleveland, OH

GaAs Crystal Growth Experiment

Prof. David H. Matthiesen
Case Western Reserve University
Cleveland, OH

Diffusion Processes in Molten Semiconductors

Prof. David H. Matthiesen
Case Western Reserve University
Cleveland, OH

Space- and Ground-Based Crystal Growth Using Magnetically Coupled Baffle

Dr. Aleksandar G. Ostrogorsky
Rensselaer Polytechnic Institute
Troy, NY

Comparison of Structure and Segregation in Alloys Directionally Solidified in Terrestrial and Microgravity Environments

Prof. David R. Poirier
University of Arizona
Tucson, AZ

Temperature Dependence of Diffusivities in Liquid Metals

Prof. Franz E. Rosenberger
University of Alabama, Huntsville
Huntsville, AL

Self-Diffusion in Liquid Elements

Prof. Franz E. Rosenberger
University of Alabama, Huntsville
Huntsville, AL

Particle Engulfment and Pushing by Solidifying Interfaces

Dr. Doru M. Stefanescu
University of Alabama
Tuscaloosa, AL

Crystal Growth of ZnSe and Related Ternary Compound Semiconductors by Physical Vapor Transport

Dr. Ching-Hua Su
NASA MSFC
Marshall Space Flight Center, AL

Interface Pattern Selection Criterion for Cellular Structures in Direction Solidification

Dr. Rohit K. Trivedi
Iowa State University
Ames, IA

Coarsening in Solid-Liquid Mixtures

Prof. Peter W. Voorhees
Northwestern University
Evanston, IL

Vapor Growth of Alloy-Type Semiconductor Crystals

Dr. Heribert Wiedemeier
Rensselaer Polytechnic Institute
Troy, NY

Ground-Based Experiments

Analysis of Residual Acceleration Effects on Transport and Segregation During Directional Solidification of Tin-Bismuth in the MEPHISTO Furnace Facility

Prof. J. Iwan D. Alexander
University of Alabama, Huntsville
Huntsville, AL

Synthesis and Characterization of Single Macromolecules: Mechanistic Studies of Crystallization and Aggregation

Dr. Spiro D. Alexandratos
University of Tennessee
Knoxville, TN

Microgravity Impregnation of Fiber Preforms

Dr. M.C. Altan
University of Oklahoma
Norman, OK

An Electrochemical Method to Visualize Flow and Measure Diffusivity in Liquid Metals

Dr. Timothy J. Anderson
University of Florida
Gainesville, FL

A Novel Electrochemical Method for Flow Visualization

Dr. Timothy J. Anderson
University of Florida
Gainesville, FL

The Effects of Convection on Morphological Stability During Coupled Growth in Immiscible Systems

Dr. J.B. Andrews
University of Alabama, Birmingham
Birmingham, AL

Foam Metallic Glasses

Prof. Robert E. Apfel
Yale University
New Haven, CT

Ostwald Ripening of Liquid and Solid Droplets in Liquid Metal Matrices

Dr. Alan J. Ardell
University of California, Los Angeles
Los Angeles, CA

Nucleation and Cluster Formation in Levitated Droplets

Prof. Stephen Arnold
Polytechnic University, New York
Brooklyn, NY

Molecularly Tailored Surfaces via Self-Assembly Processes: Synthesis, Characterization and Modeling

Dr. Mark A. Barteau
University of Delaware
Newark, DE

Studies of Nucleation and Growth of Intermetallic Compounds

Dr. Robert J. Bayuzick
Vanderbilt University
Nashville, TN

Transport Phenomena During Equiaxed Solidification of Alloys

Prof. Christoph Beckermann
University of Iowa
Iowa City, IA

Equiaxed Dendritic Solidification Experiment

Prof. Christoph Beckermann
University of Iowa
Iowa City, IA

Gravitational Effects on the Development of Weld-Pool and Solidification Microstructures in Metal Alloy Single Crystals

Dr. Lynn A. Boatner
Oak Ridge National Laboratory
Oak Ridge, TN

Dispersion Microstructure and Rheology in Ceramics Processing

Dr. John F. Brady
California Institute of Technology
Pasadena, CA

Combustion Synthesis of Materials in Microgravity

Dr. Kenneth Brezinsky
University of Illinois, Chicago
Chicago, IL

Modeling of Convection and Crystal Growth in Directional Solidification of Semiconductor and Oxide Crystals

Dr. Robert A. Brown
Massachusetts Institute of Technology
Cambridge, MA

Microstructure Formation During Directional Solidification of Binary Alloys Without Convection: Experiment and Computation

Dr. Robert A. Brown
Massachusetts Institute of Technology
Cambridge, MA

Application of Parallel Computing for Two- and Three-Dimensional Modeling of Bulk Crystal Growth and Microstructure Formation

Dr. Robert A. Brown
Massachusetts Institute of Technology
Cambridge, MA

Evolution of Crystal and Amorphous Phase Structure During Processing of Thermoplastic Polymers

Prof. Peggy Cebe
Tufts University
Medford, MA

Optical Properties for High-Temperature Materials Research

Dr. Ared Cezairliyan
National Institute of Standards and Technology
Gaithersburg, MD

Thermophysical Properties of High-Temperature Liquid Metals and Alloys

Dr. Ared Cezairliyan
National Institute of Standards and Technology
Gaithersburg, MD

Three-Dimensional Velocity Field Characterization in a Bridgman Apparatus: Technique Development and Effect Analysis

Dr. Soyoung S. Cha
University of Illinois, Chicago
Chicago, IL

Microgravity Chemical Vapor Deposition

Dr. Ivan O. Clark
NASA LaRC
Hampton, VA

Glass Formation and Nucleation in Microgravity: Containerless-Processed, Inviscid Silicate/Oxide Melts (Ground-Based Studies)

Dr. Reid E. Cooper
University of Wisconsin, Madison
Madison, WI

Fundamental Studies of Solidification in Microgravity Using Real-Time X-Ray Microscopy

Dr. Peter A. Curreri
NASA MSFC
Marshall Space Flight Center, AL

Directional Solidification in ³He-⁴He Alloys

Prof. Arnold Dahm
Case Western Reserve University
Cleveland, OH

Adaptive-Grid Methods for Phase Field Models of Microstructure Development

Dr. Jonathan A. Dantzig
University of Illinois, Urbana-Champaign
Urbana, IL

Atomistic Simulations of Cadmium Telluride: Toward Understanding the Benefits of Microgravity Crystal Growth

Dr. Jeffrey J. Derby
University of Minnesota
Minneapolis, MN

Use of Synchrotron White Beam X-Ray Topography for the Characterization of the Microstructural Development of Crystal—Normal Gravity Versus Microgravity

Dr. Michael Dudley
State University of New York, Stony Brook
Stony Brook, NY

Combined Synchrotron White Beam X-Ray Topography and High Resolution Triple Axis X-Ray Diffraction Characterization and Analysis of Crystals Grown in Microgravity and Ground Based Experiments

Dr. Michael Dudley
State University of New York, Stony Brook
Stony Brook, NY

Reverse Micelle Based Synthesis of Microporous Materials in Microgravity

Prof. Prabir K. Dutta
Ohio State University
Columbus, OH

Studies on Nucleation, Polymerization, and Nanoparticle Composites in Supersaturated Vapors Under Microgravity Conditions

Dr. M.S. El-Shall
Virginia Commonwealth University
Richmond, VA

Theoretical and Experimental Investigation of Vibrational Control of the Bridgman Crystal Growth Technique

Dr. Alexandre I. Fedoseyev
University of Alabama, Huntsville
Huntsville, AL

The Impaction, Spreading, and Solidification of a Partially Solidified Undercooled Drop

Dr. Merton C. Flemings
Massachusetts Institute of Technology
Cambridge, MA

Investigation of Local Effects on Microstructure Evolution

Dr. Donald O. Frazier
NASA MSFC
Marshall Space Flight Center, AL

Melt Stabilization of PbSnTe in a Magnetic Field

Dr. Archibald L. Frupp
NASA LaRC
Hampton, VA

Solidification of II-VI Compounds in a Rotating Magnetic Field

Dr. Donald C. Gillies
NASA MSFC
Marshall Space Flight Center, AL

Electronic Materials

Mr. Thomas K. Glasgow
NASA LeRC
Cleveland, OH

Effect of Gravity on the Evolution of Spatial Arrangement of Features in Microstructure: A Quantitative Approach

Prof. Arun M. Gokhale
Georgia Institute of Technology
Atlanta, GA

Evolution of Microstructural Distance Distributions in Normal Gravity and Microgravity

Prof. Arun M. Gokhale
Georgia Institute of Technology
Atlanta, GA

Plasma Dust Crystallization

Dr. John A. Goree
University of Iowa
Iowa City, IA

Utilizing Controlled Vibrations in a Microgravity Environment to Understand and Promote Microstructural Homogeneity During Floating-Zone Crystal Growth

Dr. Richard N. Grugel
Universities Space Research Association
Marshall Space Flight Center, AL

Novel Directional Solidification Processing of Hypermonotectic Alloys

Dr. Richard N. Grugel
Universities Space Research Association
Marshall Space Flight Center, AL

Influence of Free Convection in Dissolution

Prof. Prabhat K. Gupta
Ohio State University
Columbus, OH

Microgravity Processing of Oxide Superconductors

Dr. William H. Hofmeister
Vanderbilt University
Nashville, TN

Dimensional Stability of Supermatrix Semiconductors

Dr. Douglas E. Holmes
Electronic Materials Engineering
Camarillo, CA

Non-Equilibrium Phase Transformations

Dr. Kenneth A. Jackson
University of Arizona
Tucson, AZ

Dislocation Formation During Growth of Semiconductor Crystals

Dr. Monica L. Kaforey
Case Western Reserve University
Cleveland, OH

The Role of Dynamic Nucleation at Moving Boundaries in Phase and Microstructure Selection

Dr. Alain S. Karma
Northeastern University
Boston, MA

Identification of Gravity-Related Effects on Crystal Growth From Melts

With an Immiscibility Gap
Dr. Mohammad Kassemi
Ohio Aerospace Institute
Cleveland, OH

Combined Heat Transfer Analysis of Crystal Growth

Dr. Mohammad Kassemi
Ohio Aerospace Institute
Cleveland, OH

Measurement of Liquid-to-Solid Nucleation Rates in Undercooled Metallic Melts

Dr. Joseph L. Katz
Johns Hopkins University
Baltimore, MD

Fundamentals of Thermomigration of Liquid Zones Through Solids

Prof. Michael J. Kaufman
University of Florida
Gainesville, FL

Compositional Dependence of Phase Formation and Stability

Dr. Kenneth F. Kelton
Washington University, St. Louis
St. Louis, MO

Phase Formation and Stability: Composition and Sample-Size Effects

Dr. Kenneth F. Kelton
Washington University, St. Louis
St. Louis, MO

Solutocapillary Convection Effects on Polymeric Membrane Morphology

Dr. William B. Krantz
University of Colorado, Boulder
Boulder, CO

Influence of Natural Convection and Thermal Radiation on Multi-Component Transport and Chemistry in MOCVD Reactors

Dr. Anantha Krishnan
CFD Research Corporation
Huntsville, AL

Containerless Property Measurement of High-Temperature Liquids

Dr. Shankar Krishnan
Containerless Research, Inc.
Evanston, IL

Noise and Dynamical Pattern Selection in Solidification

Prof. Douglas A. Kurtze
North Dakota State University
Fargo, ND

Study of Magnetic Damping Effect on Convection and Solidification Under G-Jitter Conditions

Dr. Ben Q. Li
Louisiana State University
Baton Rouge, LA

Microstructural Development During Directional Solidification of Peritectic Alloys

Dr. Thomas A. Lograsso
Iowa State University
Ames, IA

Numerical Investigation of Thermal Creep and Thermal Stress Effects in Microgravity Physical Vapor Transport

Dr. Daniel W. Mackowski
Auburn University
Auburn, AL

Polymerizations in Microgravity: Traveling Fronts, Dispersions, Diffusion, and Copolymerizations

Dr. Lon J. Mathias
University of Southern Mississippi
Hattiesburg, MS

Quantitative Analysis of Crystal Defects by Triple Crystal X-Ray Diffraction

Dr. Richard J. Matyi
University of Wisconsin, Madison
Madison, WI

Numerical and Laboratory Experiments on the Interactive Dynamics of Convection, Flow, and Directional Solidification

Prof. Tony Maxworthy
University of Southern California
Los Angeles, CA

The Interactive Dynamics of Convection, Flow, and Directional Solidification

Prof. Tony Maxworthy
University of Southern California
Los Angeles, CA

Y_2BaCuO_5 Segregation in $YBa_2Cu_3O_{7-x}$ During Melt Texturing

Dr. Paul J. McGinn
University of Notre Dame
Notre Dame, IN

Interaction of Hele-Shaw Flows With Directional Solidification: Numerical Investigation of the Nonlinear Dynamical Interplay and Control Strategies

Prof. Eckart H. Meiburg
University of Southern California
Los Angeles, CA

The Synergistic Effect of Ceramic Materials Synthesis Using Vapor-Enhanced Reactive Sintering Under Microgravity Conditions

Prof. John J. Moore
Colorado School of Mines
Golden, CO

Diffusion, Viscosity, and Crystal Growth in Microgravity

Dr. Allan S. Myerson
Polytechnic University, New York
Brooklyn, NY

An Electrochemical Method to Measure Diffusivity in Liquid Metals

Prof. Ranga Narayanan
University of Florida
Gainesville, FL

Crystal Growth and Segregation Using the Submerged Heater Method

Dr. Aleksandar G. Ostrogorsky
Rensselaer Polytechnic Institute
Troy, NY

Gravitational Effects on the Morphology and Kinetics of Photo-Deposition of Polydiacetylene Films From Monomer Solutions

Dr. Mark S. Paley
Universities Space Research Association
Marshall Space Flight Center, AL

Investigation of "Contactless" Crystal Growth by Physical Vapor Transport

Dr. Witold Palosz
Universities Space Research Association
Marshall Space Flight Center, AL

Investigation of Convective Effects in Crystals Growth by Physical Vapor Transport

Dr. Witold Palosz
Universities Space Research Association
Marshall Space Flight Center, AL

Containerless Processing of Composite Materials

Prof. John H. Perepezko
University of Wisconsin, Madison
Madison, WI

Analysis of Containerless Processing and Undercooled Solidification Microstructures

Prof. John H. Perepezko
University of Wisconsin, Madison
Madison, WI

Containerless Processing for Controlled Solidification Microstructures

Prof. John H. Perepezko
University of Wisconsin, Madison
Madison, WI

Comparison of the Structure and Segregation in Dendritic Alloys Solidified in Terrestrial and Low Gravity Environments

Prof. David R. Poirier
University of Arizona
Tucson, AZ

The Effects of Microgravity on Vapor Phase Sintering

Prof. Dennis W. Readey
Colorado School of Mines
Golden, CO

Modeling of Detached Solidification

Dr. Liya L. Regel
Clarkson University
Potsdam, NY

Thermophysical Property Measurement of Molten Semiconductors in 1-g and Reduced-g Conditions

Dr. Won-Kyu Rhim
NASA JPL
Pasadena, CA

Undercooling Limits and Thermophysical Properties in Glass Forming Alloys

Dr. Won-Kyu Rhim
NASA JPL
Pasadena, CA

Drop Tube Operation

Dr. Michael B. Robinson
NASA MSFC
Marshall Space Flight Center, AL

Measurement of the Optical and Radiative Properties of High-Temperature Liquid Materials by FTIR Spectroscopy

Dr. Michael B. Robinson
NASA MSFC
Marshall Space Flight Center, AL

A Study of the Undercooling Behavior of Immiscible Metal Alloys in the Absence of Crucible-Induced Nucleation

Dr. Michael B. Robinson
NASA MSFC
Marshall Space Flight Center, AL

Determination of the Surface Energy of Liquid Crystals From the Shape Anisotropy of Freely Suspended Droplets

Dr. Charles S. Rosenblatt
Case Western Reserve University
Cleveland, OH

Modeling of Macroscopic/Microscopic Transport and Growth Phenomena in Zeolite Crystal Solutions Under Microgravity

Dr. Albert Sacco
Worcester Polytechnic Institute
Worcester, MA

Undercooling Limits in Molten Semiconductors and Metals: Structure and Superheating Dependencies

Prof. Frank G. Shi
University of California, Irvine
Irvine, CA

Gravitational Effect on the Development of Laser Weld-Pool and Solidification Microstructure

Dr. Jogender Singh
Pennsylvania State University
University Park, PA

Flight Experiment to Study Double Diffusive Instabilities in Silver-Doped Lead Bromide Crystals

Dr. N.B. Singh
Northrop-Grumman Corporation
Pittsburgh, PA

Double Diffusive Convection During Growth of Lead Bromide Crystals

Dr. N.B. Singh
Northrop-Grumman Corporation
Pittsburgh, PA

Kinetics of Nucleation and Growth From Undercooled Melts

Prof. Frans A. Spaepen
Harvard University
Cambridge, MA

Crystal Nucleation, Hydrostatic Tension, and Diffusion in Metal and Semiconductor Melts

Prof. Frans A. Spaepen
Harvard University
Cambridge, MA

Micro- and Macro-Segregation in Alloys Solidifying With Equiaxed Morphology

Dr. Doru M. Stefanescu
University of Alabama
Tuscaloosa, AL

Test of Magnetic Damping of Convective Flows in Microgravity

Dr. Frank R. Szofran
NASA MSFC
Marshall Space Flight Center, AL

Magnetic Damping of Solid Solution Semiconductor Alloys

Dr. Frank R. Szofran
NASA MSFC
Marshall Space Flight Center, AL

The Features of Self-Assembling Organic Bilayers Important to the Formation of Anisotropic Inorganic Materials in Microgravity Conditions

Dr. Daniel R. Talham
University of Florida
Gainesville, FL

Microporous Membrane and Foam Production by Solution Phase Separation: Effects of Microgravity and Normal Gravity Environments on Evolution of Phase Separated Structures

Dr. John M. Torkelson
Northwestern University
Evanston, IL

Dynamically-Induced Nucleation of Deeply Supercooled Melts and Measurement of Surface Tension and Viscosity

Dr. Eugene H. Trinh
NASA JPL
Pasadena, CA

A Proposal to Further Investigate the Influence of Microgravity on Transport Mechanisms in a Virtual Space Flight Chamber

Dr. James D. Trolinger
MetroLaser, Inc.
Irvine, CA

Fundamentals of Mold-Free Casting Experimental and Computational Studies

Prof. Grétar Tryggvason
University of Michigan
Ann Arbor, MI

Electromagnetic Field Effects in Semiconductor Crystal Growth

Dr. Martin P. Volz
NASA MSFC
Marshall Space Flight Center, AL

Models of Magnetic Damping for Semiconductor Crystal Growth in Microgravity

Dr. John S. Walker
University of Illinois, Urbana-Champaign
Urbana, IL

Process-Property-Structure Relationships in Complex Oxide Melts

Dr. Richard Weber
Containerless Research, Inc.
Evanston, IL

Thin Film Mediated Phase Change Phenomena: Crystallization, Evaporation, and Wetting

Prof. John S. Wettlaufer
University of Washington
Seattle, WA

Defect Generation in CVT Grown Hg_{1-x}Cd_xTe Epitaxial Layers Under Normal and Reduced Gravity Conditions

Dr. Heribert Wiedemeier
Rensselaer Polytechnic Institute
Troy, NY

Use of Microgravity to Control the Microstructure of Eutectics

Dr. William R. Wilcox
Clarkson University
Potsdam, NY

BSO/BTO Identification of Gravity Related Effects on Crystal Growth, Segregation, and Defect Formation

Dr. August F. Witt
Massachusetts Institute of Technology
Cambridge, MA

Technology, Hardware, and Education Outreach

Advanced Technology Development 1996

The Advanced Technology Development (ATD) Program was developed by NASA's Microgravity Science and Applications Division (MSAD) in response to the challenges researchers face when defining experiment requirements and designing associated hardware. Investing in technology development is necessary if the United States intends to remain a top competitor in future scientific research. ATD researchers help ensure that the Nation continues its forward strides in the fields of technology development and scientific experimentation.

Technology development projects are designed to address scientific concerns, both focused and broadly based. Focused development projects ensure the availability of technologies that satisfy the science requirements of specific flight- or ground-based programs. Broadly based development

projects encompass a long-term, proactive approach to meeting the needs of future projects and missions, such as human exploration and development of space.

MSAD solicits new ATD projects each year and selects the very best for funding. New ATD projects are solicited through a two-step process, for which NASA centers are eligible. First, concept papers are solicited from each NASA Center involved in microgravity research. Next, the MSAD Director and ATD Program Manager form an ATD Review Panel, consisting of microgravity science representatives from each NASA Center and from the MSAD Science Program at NASA HQ. The panel reviews concept papers for their technical merit and significance to the microgravity field and selects candidates for further consideration.

These successful candidates must submit fully detailed ATD proposals. These proposals are peer-reviewed by experts in corresponding technology areas who are selected from non-NASA organizations. Final selections are made based on the panel's recommendations on the relevance to the anticipated technology needs of the Microgravity Research Science Program, potential for success, and the potential for the project to enable new types of microgravity investigations.

A listing of ATD tasks funded by MSAD in FY 1996 is given in table 7. Further details on these tasks may be found in the complementary document *Microgravity Science and Applications Program Tasks and Bibliography for FY 1996*, NASA Technical Memorandum 4780, March 1997.

TABLE 7.—ATD tasks funded by MSAD in FY 1996.

Free Float Trajectory Management ATD

Mr. A.P. Allan
University of Delaware
Wilmington, DE

Single Electron Transistor (SET)

Dr. Pierre Echternach
NASA JPL
Pasadena, CA

Microgravity Combustion Diagnostics

Mr. Paul S. Greenberg
NASA LeRC
Cleveland, OH

Low Temperature Magnetostrictive Smart Actuator Mechanisms

Dr. Robert G. Chave
NASA JPL
Pasadena, CA

Advanced Heat Pipe Technology for Furnace Element Design

Dr. Donald C. Gillies
NASA MSFC
Marshall Space Flight Center, AL

High Resolution Pressure Transducer and Controller

Dr. Ulf E. Israelsson
NASA JPL
Pasadena, CA

Real-Time X-Ray Microscopy for Solidification Processing

Dr. Peter A. Curreri
NASA MSFC
Marshall Space Flight Center, AL

Space Bioreactor Bioproduct Recovery System

Dr. Steve R. Gonda, Ph.D.
NASA JSC
Houston, TX

Surface Fluctuation Spectrometers for the Characterization of Fluid and Crystal Surfaces

Mr. William V. Meyer
Ohio Aerospace Institute
Cleveland, OH

The Laser Feedback Interferometer: A New, Robust, and Versatile Tool for Measurements of Fluid Physics Phenomena

Dr. Ben Ovryn
NYMA, Inc.
Cleveland, OH

Crystal Growth Instrumentation Development: A Protein Crystal Growth Studies Cell

Dr. Marc L. Pusey
NASA MSFC
Marshall Space Flight Center, AL

High-Resolution Thermometry and Improved SQUID Readout

Dr. Peter Shirron
NASA GSFC
Greenbelt, MD

Passive Free Vortex, Two-Phase Separator

Dr. J.M. Shoemaker
Aerospace Design and Fabrication, Inc.
Brookpark, OH

Determination of Soot Volume Fraction Using Laser-Induced Incandescence

Dr. Randall L. Vander Wal
NASA LeRC
Cleveland, OH

Ceramic Cartridges via Sintering and Vacuum Plasma Spray

Mr. Frank R. Zimmerman
NASA MSFC
Marshall Space Flight Center, AL

Microgravity Technology Development Goals

MSAD created the ATD Program with the intent to provide efficient, cost-effective, and ongoing support for microgravity science investigations. The primary goal of the ATD Program is to develop technology that will enable new types of scientific investigation. This goal is achieved by enhancing the capability and quality of experiment hardware available to researchers or by overcoming existing technology-based constraints to microgravity science research capabilities. The ATD Program provides opportunities to carry out the goals of NASA's Microgravity Science and Applications Program by conducting state-of-the-art technology development.

MSAD funds technology development through an initial feasibility demonstration that verifies whether or not a technology is suitable for use in either ground-based or flight programs. The goal is to investigate and develop high-risk microgravity research technologies before they are needed on the critical development path for actual flight hardware.

Depending on its state of maturity, the technology developed under the ATD Program may either make a direct transition to use in a specific ground-based or flight program, or require further development to satisfy a specific program requirement. Ideally, the successful progression or

completion of an ATD task will reduce risk and cost in the transition from ground-based research to flight hardware design and application in MSAD programs.

Scope of Projects

Historically, ATD projects have encompassed a broad range of activities. Project funding includes the development of diagnostic instrumentation and measurement techniques, observational instrumentation and data recording methods, acceleration characterization and control techniques, and advancements in methodologies associated with hardware design technology.

In FY 1996, five NASA Centers were involved in the MSAD ATD Program: Goddard Space Flight Center (GSFC), Jet Propulsion Lab (JPL), Johnson Space Center (JSC), Lewis Research Center (LeRC), and Marshall Space Flight Center (MSFC). The previous and current projects listed below illustrate the breadth of technologies covered by the ATD Program.

Previously Funded ATD Projects

Several previously funded ATD projects have been selected for further development under MSAD's Technology Transfer Program. Under this program, research conducted for the ATD Program is

targeted for transfer to the industrial and research communities. Examples of technologies derived from previous ATD projects are given below.

Advanced Furnace Technology (LeRC).

Researchers for this project examined means of controlling thermal gradients and interface shapes in crystal growth. The project provided the foundation for a compact furnace design used for the Coarsening of Solid-Liquid Mixtures flight development project. This furnace achieves the isothermality and tight thermal control required by investigators, yet is compact enough to fit in the Glovebox on board the space shuttle. This design supplants previous plans to build a special middeck-sized furnace, saving NASA several million dollars and enabling the science to be performed sooner than anticipated.

Some of the work conducted under the ATD program also contributed to the NASA-funded Programmable Multizone Furnace (PMZF) project. Ground-based research in support of a flight-definition project entitled Diffusion Processes in Molten Semiconductors is being carried out in the PMZF, which was made possible by this ATD technology.

Laser Light Scattering (LeRC). Laser light scattering is a technique used to characterize very small particles by size, shape, and tendency to associate. This project enabled scientists to optically and noninvasively

measure particle sizes in fluids, using a compact instrument suitable for microgravity experimentation. This miniature laser light scattering unit, based on fiber optic technology, allows microgravity investigations to be conducted in such areas as critical-point studies, nucleation, spinodal decomposition, gelation and diffusion. The instrument has already been used to study Colloidal Disorder-Order Transitions in a flight experiment, the results of which were unanticipated from ground-based research. A variety of other experiments, including the Physics of Hard Spheres Experiment, is scheduled to fly aboard the space shuttle. In addition, LeRC is helping to design the Fluids and Combustion Facility (FCF) to accommodate laser light scattering experiments on the *ISS*.

Laser light scattering technology has also proven its value in other fields. LeRC researchers, working with the University of Alabama, are designing special "in the droplet" probes to be used in protein crystal growth flight experiments. The team has also helped to define another design, which will perform simultaneous multi-angle scattering from proteins growing in gels. In addition, the compact light scattering instrument may have potential use as a diagnostic tool for cataracts. MSAD is collaborating with the NIH to use the tool to detect early signs of the onset of cataract formation.

Microwave Furnace Development for Materials Processing (JPL). This project developed a high-efficiency, cold-wall, direct-heating furnace that features enhanced tuning techniques and allows for the rapid heating and cooling of ceramics and metals. This microwave furnace is unique in two ways: it has the ability to heat the interior of materials, and the furnace's power can be continuously adjusted to provide fast and precise time-temperature heating profiles. The new heating techniques will be used for containerless material processing in space.

Theoretical models developed under the ATD Program have also been used to show that improved materials processing is possible by using microwave energy to heat ceramics. These analytical models can accurately describe the microwave-materials interaction taking place in the furnace and can predict the temperature profiles within spherical and cylindrical samples.

The researchers at JPL are in the process of transferring this technology to the private sector. They have signed four Technology Cooperation Agreements: (1) Golden Technologies, Inc., for a project entitled Microwave Joining of High-Temperature Ceramics Using an SHS Materials Interlayer; (2) Lambda Technologies, Inc., for a project entitled Modeling of Microwave Processing Parameters for Variable-Frequency Furnaces Under Various Load Conditions; (3) Communications and Power Industries, for a project entitled Modeling of Microwave Processing Parameters for Samples and Reactors of Various Sizes and Shapes; and (4) Supercond Technology, Inc., for a project entitled Microwave Curing of Carbon-Carbon Composites.

Stereo Imaging Velocimetry (LeRC).

Research in this area provided a method to measure three-dimensional fluid velocities quantitatively and simultaneously by mapping and tracking multiple tracer particles whose locations were determined from two camera images. The three-dimensional vector output of stereo imaging velocimetry (SIV) may be compared directly with the output of numerical models. Uses of this technology in microgravity research include a fluid physics experiment to monitor flow around a bubble during nucleate boiling heat transfer and the combustion flight experiment Structure of Flame Balls at Low Lewis Number (SOFBALL), in which cellular flame propagation will be studied.

SIV has also been used outside of NASA in industrial research. LTV Steel is using SIV

to characterize flows in continuous steel casting, using water models. Under a NASA-LTV Space Act Agreement funded by the Lewis Technology Utilization Office, LeRC helped LTV improve their water model and obtain data which they have used to support capital investment decisions. SIV equipment may also be installed at the University of Toledo to serve the needs of its industrial area. Toledo companies showing strong interest in this possibility include Teledyne, Surface Combustion, and Toledo Mold and Die.

1996 Advanced Technology Development Projects

Advanced Heat Pipe Technology for Furnace Element Design in Spaceflight Applications (MSFC). The goal of this project is to develop a heat pipe that will operate as an isothermal furnace liner capable of processing materials at temperatures up to 1,500 °C. The isothermal furnace liner is intended for use aboard the *ISS* and for ground-based materials science investigations in which precise temperature control is beneficial.

Advancement of Solidification Processing Through Real-Time X-Ray Microscopy (MSFC). Under this ATD project, a high-resolution x-ray microscope is being developed to view, in situ and in real time, the interfacial processes in metallic systems during freezing (solidification). Research goals of this project include studying the solidification of metals and semiconductors and the dispersion of reinforcement particles in composites.

Determination of Soot Volume Fraction Via Laser-Induced Incandescence (LeRC). Laser-induced incandescence (LII) is being studied for use as a two-dimensional imaging diagnostic tool for the measurement of soot volume fraction in microgravity research. LII, which is theoretically predicted to be a measure of soot volume fraction, is more accurate than current line-of-sight measurement techniques.

Free-Float Trajectory Management

(LeRC). The objective of this technology is to produce an extended, consistently reproducible, cost-efficient acceleration environment, specifically for free-float packages, during the stabilized low-gravity phase of the flight trajectory of the NASA DC-9 reduced-gravity aircraft, which serves as a test environment for micro-gravity investigations. The controller monitors the location of the package and sends control commands to the pilots, which enable them to fly the aircraft about the trajectory of the package.

High-Resolution Pressure Transducer and Controller (JPL).

High-resolution pressure transducers and controllers are being developed under this ATD project to provide improved performance over those currently available. These devices will be combined with high-resolution thermometers to enable researchers to precisely measure and control both pressure and temperature in their investigations.

High-Resolution Thermometry and Improved SQUID Readout (GSFC).

This research will develop a high-resolution penetration depth thermometer using a Two-Stage Series Array SQUID Amplifier (TSSA) for readout. The TSSA will overcome problems caused by thermal fluctuations and particle radiation which occur in measuring and controlling the thermodynamic state of samples, particularly in the microgravity environment.

Laser Feedback Interferometer (LeRC).

This project will develop an instrument that will use a laser as both a light source and a phase detector in order to measure phenomena which vary slowly over time and dynamic phenomena over both microscopic and macroscopic fields of view. This technology has applications in several scientific fields, including biomedical engineering, chemistry, materials science, mechanical engineering, and physics.

Low-Temperature Magnetostrictive Smart Actuator Mechanisms (JPL).

Under this ATD project, magnetostrictive materials will be developed into liquid helium valve actuators, cryogenic heat switches, linear actuators for variable volume calorimeters, and other devices for use at low temperature. Magnetostrictive drive will enhance the effectiveness of liquid and superfluid helium valves.

Manufacturing of Refractory Containment Cartridges (MSFC).

Plasma spray is being used to form multiple layer containment cartridges, consisting of combinations of refractory metals and ceramics, for use in single-crystal growth studies. The monolithic cartridges can be formed from the best combination for each particular application and will be designed to meet a demanding set of requirements, including high service temperature, oxidation resistance, and resistance to liquid semiconductor attack.

Microgravity Combustion Diagnostics

(LeRC). In order to improve the diagnostic techniques available to microgravity combustion scientists, the following technologies, which promote nonintrusive techniques, are being investigated under this ATD project: two-dimensional temperature and species measurement, exciplex fluorescence for droplet diagnostics, full-field infrared emission imaging, and velocity field diagnostics.

Passive Free-Vortex Separator (LeRC).

Future long-term experiments will require that gas-liquid mixtures be separated into single-phase states prior to reuse or recycling. The passive free-vortex separator will be developed under this ATD project to separate two-phase fluid mixtures in microgravity.

Protein Crystal Growth Studies Cell

(MSFC). Under this ATD project, a user-friendly system for conducting real-time innovative PCG research in the microgravity environment will be developed,

along with a method for storing proteins prior to use in experiments. Researchers will be able to control the PCG system from the ground, adjust the parameters of their experiments, and perform follow-up experiments based on previous results, enabling a more rigorous study of the PCG process than is currently possible.

Space Bioreactor Bioproduct Recovery System (JSC).

The current generation of space bioreactors can support some aspects of long-duration cell cultures, but cannot be used to separate and preserve or remove the bioproducts of these processes. The goal of this project is to develop a bioproduct recovery system that allows the selective removal of molecules of interest from space bioreactors, thus enhancing their productivity.

Surface Fluctuation Spectrometers

(LeRC). During this project, a surface light scattering instrument using fiber-optics-based technology will be developed to provide a noninvasive way to obtain surface tension, viscosity, and temperature data from fluid interfaces. The instrument will also be able to measure displacements of solid surfaces, such as those encountered in crystal growth.

Microgravity Technology Report

In December 1995, NASA's first *Microgravity Technology Report* was published. This document covers technology policies, technology development, and technology transfer activities within the Microgravity Science Research Program from 1978 through FY 1994. It also describes the recent major tasks initiated under the ATD Program and identifies current technology requirements. The *FY 1996 Annual Microgravity Technology Report* is available as a companion to this annual Microgravity Science Research Program report.

Hardware

Experiment Hardware for Space Shuttle and Mir Flights

Significant efforts continued in FY 1996 in preparation of multiuser and experiment-unique apparatus for space shuttle and *Mir*

missions. Listed in table 8 are shuttle missions with significant microgravity experiments, followed by short descriptions of the U.S.-developed flight experimental apparatus that have been in use and are under development

in the Microgravity Science Research Program to support these missions. A list of flight experimental hardware being developed by international partners, which will be used by U.S. investigators, appears in table 9.

TABLE 8.—*Shuttle missions with major microgravity equipment on board, chronologically by launch date.*

Launch Date	Flight	Mission	Full Name
April 1985	STS-51B	SL-3	Spacelab-3
Jan. 1986	STS-61C		Materials Science Demonstrations
Jan. 1992	STS-42	IML-1	International Microgravity Laboratory-1
June 1992	STS-50	USML-1	United States Microgravity Laboratory-1
Oct. 1992	STS-52	USMP-1	United States Microgravity Payload-1
March 1994	STS-62	USMP-2	United States Microgravity Payload-2
July 1994	STS-65	IML-2	International Microgravity Laboratory-2
June 1995	STS-71	<i>Mir</i> -1	Shuttle/ <i>Mir</i> -1
Sept. 1995	STS-69	*	Wake Shield Facility, Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN)
Oct. 1995	STS-73	USML-2	United States Microgravity Laboratory-2
Nov. 1995	STS-74	<i>Mir</i> -2	Shuttle/ <i>Mir</i> -2
Feb. 1996	STS-75	USMP-3	United States Microgravity Payload-3
March 1996	STS-76	<i>Mir</i> -3	Shuttle/ <i>Mir</i> -3
June 1996	STS-78	LMS	Life and Microgravity Spacelab
Sept. 1996	STS-79	<i>Mir</i> -4	Shuttle/ <i>Mir</i> -4
Jan. 1997	STS-81	<i>Mir</i> -5	Shuttle/ <i>Mir</i> -5
April 1997	STS-83	MSL-1	Microgravity Science Laboratory-1
May 1997	STS-84	<i>Mir</i> -6	Shuttle/ <i>Mir</i> -6
July 1997	STS-83R	MSL-1R	Microgravity Science Laboratory-Space Reflight
Aug. 1997	STS-85		CRISTA-SPAS-2, Japanese Experiment Module Flight Demonstration
Sept. 1997	STS-86	<i>Mir</i> -7	Shuttle/ <i>Mir</i> -7
Nov. 1997	STS-87	USMP-4	United States Microgravity Payload-4
Feb. 2001	STS-113	MSP-1	Microgravity Science Payload-1

*Middeck and GAS microgravity payloads only.

GAS payloads also flew on STS-40, -41, -43, -45, -47, -54, -57, -60, -63, -64, -66, -72, and -77.

TABLE 9.—*Flight experiment hardware used by NASA's Microgravity Science Research Program developed by international partners.*

Advanced Gradient Heating Furnace	European Space Agency (ESA)
Advanced Protein Crystallization Facility	European Space Agency (ESA)
Bubble, Drop, and Particle Unit	European Space Agency (ESA)
Biolab	German Agency for Space Affairs (DARA)
Critical Point Facility	European Space Agency (ESA)
Cryostat	German Agency for Space Affairs (DARA)
Electromagnetic Containerless Processing Facility (TEMPUS)	German Agency for Space Affairs (DARA)
Electrophoresis, Recherché Appliqué Sur Les Methods	
De Separation en Electrophorese Spatiale (RAMSES)	French National Center for Space Studies (CNES)
Free Flow Electrophoresis Unit	National Space Development Agency of Japan (NASDA)
Gloveboxes*	European Space Agency (ESA)
Large Isothermal Furnace	National Space Development Agency of Japan (NASDA)
MEPHISTO	French National Center for Space Studies (CNES)
Microgravity Isolation Mount	Canadian Space Agency (CSA)
Mirror Furnace	National Space Development Agency of Japan (NASDA)
Microgravity Measurement Assembly	European Space Agency (ESA)
Quasi-Steady Acceleration Measurement	German Agency for Space Affairs (DARA)

*Middeck Glovebox, *Mir* Glovebox, and Microgravity Glovebox (Spacelab)

Advanced Automated Directional Solidification Furnace. This instrument is a modified Bridgman-Stockbarger furnace for directional solidification and crystal growth (USMP-2, -3, -4).

Bioreactor Demonstration Unit. This unit flew on STS-70 and on STS-79 to the *Mir*. It is a rotating cylinder bioreactor for the investigation of tissue engineering, supported by subsystems that provide perfusion, medium exchange, pH monitoring, and data storage (*Mir*).

Biotechnology Specimen Temperature Controller. This is a programmable cell culture incubator that can be used for flight experiments in cell biology, microbiology, and tissue engineering. The current version has four individually controlled chambers with a temperature range of 4 to 45 °C (shuttle/*Mir*).

Biotechnology System. This instrument is composed of a rotating wall vessel bioreactor, a control computer, a fluid supply system, and a refrigerator for sample storage (*Mir*).

Combustion Module-1. This module is being developed to perform multiple combustion experiments in space; the first two experiments will be the Laminar Soot Processes experiment and the SOFBALL experiment (MSL-1).

Critical Fluid Light Scattering Experiment. This apparatus provides a micro-Kelvin controlled thermal environment and dynamic light scattering and turbidity measurements for critical fluid experiments (USMP-2, -3).

Critical Viscosity of Xenon. This apparatus provides a precision controlled thermal environment (micro-Kelvin) and an oscillating screen viscometer to enable viscosity measurements for critical fluids (STS-85).

Crystal Growth Furnace. This instrument is a modified Bridgman-Stockbarger furnace for crystal growth from a melt or vapor (USML-1, -2).

Drop Physics Module. This apparatus is designed to investigate the surface properties of various suspended liquid drops, to study surface and internal features of drops

that are being vibrated and rotated, and to test a new technique for measuring surface tension between two immiscible fluids (USML-1, -2).

Droplet Combustion Experiment. The apparatus is designed to study droplet behavior during combustion by measuring burning rates, extinction phenomena, disruptive burning, and soot production (MSL-1).

Geophysical Fluid Flow Cell. This instrument uses electrostatic forces to simulate gravity in a radially symmetric vector field, centrally directed toward the center of the cell. This allows investigators to perform visualizations of thermal convection and other research related topics in planetary atmospheres and stars (SL-3, USML-2).

Isothermal Dendritic Growth Experiment. The apparatus is being used to study the growth of dendritic crystals in transparent materials that simulate the solidification of some aspects of pure metals and metal alloy systems (USMP- 2, -3, -4).

Low-Temperature Microgravity Physics Cryogenic Dewar. This apparatus will support different experiments on different flights. On USMP-1, supported the Lambda Point Experiment, testing the theory of confined systems using helium held near the lambda point and confined to 50-micron gaps. On USMP-4, it will support the Confined Helium Experiment. On the Microgravity Science Payload-1 (MSP-1), it supported the Critical Dynamics in Microgravity Experiment.

Mechanics of Granular Materials. This instrument uses microgravity to gain a quantitative understanding of the mechanical behavior of cohesionless granular materials under very low confining pressures (shuttle/*Mir*).

Microgravity Smoldering Combustion. This apparatus is used to determine the smoldering characteristics of combustible materials in microgravity environments (STS-69).

Middeck Glovebox. The glovebox is a multidisciplinary facility used for small scientific and technological investigations (USMP -3, -4, MSP-1).

***Mir* Glovebox.** This is a modified middeck Glovebox for collecting scientific and technological data prior to major investments in the development of more sophisticated scientific instruments (*Mir*).

Physics of Hard Spheres Experiment. This hardware will support an investigation to study the processes associated with liquid-to-solid and crystalline-to-glassy phase transitions (MSL-1).

Pool Boiling Experiment. This apparatus is capable of autonomous operation for initiating, observing, and recording nucleate pool boiling phenomena (multiple missions).

Protein Crystal Growth. PCG uses a variety of apparatus, to evaluate the effects of gravity on the growth of protein crystals, such as the Protein Crystallization Apparatus for Microgravity and the Vapor Diffusion Apparatus (multiple missions).

Solid Surface Combustion Experiment. This instrument is designed to determine the mechanism of gas-phase flame spread over solid fuel surfaces in the absence of buoyancy-induced or externally imposed gas-phase flow (multiple missions).

Space Acceleration Measurement System. SAMS measures and records the acceleration environment in the space shuttle middeck and cargo bay, in the Spacelab, SpaceHab, and on the *Mir* (multiple missions).

Surface Tension Driven Convection Experiment. The apparatus is designed to provide fundamental knowledge of thermocapillary flows, fluid motion generated by the surface attractive force induced by variations in surface tension caused by temperature gradients along a free surface (USML-1, -2).

Orbital Acceleration Research Experiment. This instrument is developed to measure very-low-frequency accelerations on orbit such as atmospheric drag and gravity gradient effects (multiple missions).

Transitional/Turbulent Gas Jet Diffusion Flames. This instrument will be used to study the role of large-scale flame structures in microgravity transitional gas jet flames (Get Away Special (GAS) Experiment).

Space Station Facilities for Microgravity Research

The Microgravity Science and Applications Research Program continues to develop several multiuser facilities specifically designed for long duration scientific research missions aboard the *ISS*. To obtain an optimal balance between science capabilities, costs, and risks, facility requirements definition have been aligned with evolving space station capabilities. In total, the Microgravity Science and Applications Research Program has now defined requirements for five multiuser facilities for the *ISS*:

- Biotechnology Facility (BTF)
- Space Station Furnace Facility (SSFF)
- Fluids and Combustion Facility (FCF)
- Microgravity Glovebox (MGBX)
- Low Temperature Microgravity Physics (LTMP) facility.

The BTF will accommodate bioreactor systems to address cell growth and systems to support PCG using the quiescent low-gravity environment of the *ISS*. In addition, this facility will handle the hardware for new areas of biotechnology research that are just beginning to be explored. Because the capabilities of the Expedite Payload Resources to Space Station (EXPRESS) rack facility were determined to be adequate to handle the needs of biotechnology research conducted during the early space station build-up phase, the development of the BTF has been delayed until later in the *ISS* operational life. This will allow for a facility more in tune with the needs of the biotechnology program at that time.

The SSFF, scheduled for operation in 2002, is designed to accommodate investigations in basic materials research, applications, and studies of phenomena involved in the solidification of metals and crystal growth of semiconductor materials. The facility is composed of furnace modules and a core of integrated support subsystems. Its development has paralleled the *ISS* design activity to ensure that payload requirements are incorporated in the *ISS* design process. The design of the core support subsystems was completed during 1996. An international workshop was held in June 1996, in Huntsville, AL, to continue dialogue between international partners on cooperative development of future furnace modules. Follow-on discussions are planned for another international workshop in mid-1997. The first U.S.-developed integrated furnace module, the High-Temperature Gradient Furnace With Quench, is scheduled for initial operations in 2002.

In FY 1995, the FCF began optimizing its engineering concept, with the intent to reduce development and life-cycle cost, and to increase life-cycle productivity. This optimization was completed during FY 1996. Development cost was cut by approximately 50 percent (in constant FY 1995 dollars). Life-cycle cost was cut by approximately 50 percent. The projected cost of individual fluids and combustion experiments was cut by approximately 60 percent. Nevertheless, scientific productivity was increased by over 150 percent (nearly tripled, as measured by the total number of experiments that may be supported in a 10-year period within all known *ISS* resource and program funding constraints). In addition, FCF capability was increased to add support for middeck payloads from any discipline and the SAMS (at no increase in project budget). A successful Requirements Definition Review was held during October 1996. Currently, FCF is operating with minimal staff through at least FY 1998. This time will be used to perform low cost technical risk mitigation experiments at LeRC. The flight date is currently to be determined, but it could be in FY 2001 or FY 2002.

Definition activities were performed during FY 1996 for the LTMP facility, a multiple-instrument facility designed for frequent flight, for easy instrument changeout to result in minimal use of *ISS* resources, and to maintain low cost. The LTMP facility was recommended for development by the National Research Council's Space Studies Board and has been endorsed by the Low-Temperature Science Steering Committee and the international low-temperature science community. The LTMP facility will be implemented through a science, industry, and NASA partnership. The industry partner, Ball Aerospace, was selected in June 1996 via a Request for Proposal process. The initial meeting of the LTMP Facility Definition Team of science, industry, and JPL representatives was conducted at JPL in July 1996.

The MGBX is a multidisciplinary facility for small, low-cost, rapid-response scientific and technological investigations in the areas of materials science, biotechnology, combustion science, and fluid physics, allowing preliminary data to be collected and analyzed prior to any major investment in sophisticated scientific and technological instrumentation. Negotiations with ESA are currently underway for the provision of the glovebox by the ESA in exchange for early

access to *ISS* capabilities. The glovebox passed system design review at ESA and, by late 1995, was in the requirements review stage. The Project Development Review is scheduled for April 1997.

In addition to the science facilities on the *ISS*, Telescience Support Centers are being developed at LeRC and MSFC to support *ISS* microgravity operations. These facilities are collocated with the hardware developers and discipline scientists to support investigators. The goal is to allow investigators to operate as much as possible from their home institutions. In FY 1994, LeRC's facility began support of ongoing shuttle missions.

Ground-Based Microgravity Research Support Facilities

NASA maintained reduced-gravity research ground facilities, including two drop towers, a drop tube, parabolic flight aircraft, and other support facilities at LeRC and MSFC, in support of the Microgravity Science Research Program. Aircraft used for parabolic flight trajectories include a KC-135 aircraft at JSC, and a DC-9 at LeRC, the latter of which began operations in July 1995. Table 10 summarizes the facilities usage in FY 1996.

TABLE 10.—*Use of ground-based low-gravity facilities—FY 1996.*

	Zero-G Facility	2.2-Second Drop Tower	Drop Tube	KC-135	DC-9
No. of Investigations Supported	7	25	8	2	42
No. of Drops or Trajectories	143	1,263	500	337	2,795
No. of Flights (Flight Hours)	N/A	N/A	N/A	7	163

Education and Outreach Activities

Thousands of elementary and secondary school teachers attending the 1996 annual meetings of the National Science Teachers Association and the National Council of Teachers of Mathematics had the opportunity to learn new ways to improve student understanding of the effects of normal and low gravity and the implications of microgravity research. More than 6,000 microgravity science educational posters, teachers guides, mathematics briefs, and supplementary materials were distributed at the conferences. Over 1,200 teachers asked to be added to the microgravity education and outreach mailing list. This brought the total number of K–12 teachers on the mailing list to 1,865 (445 kindergarten and elementary, 522 middle school, and 898 high school).

Microgravity News, the quarterly newsletter of NASA's microgravity science research programs and activities, features articles on experiment results, mission updates, science and technology developments, funding opportunities, meetings and collaborations, and profiles of microgravity

science researchers. This year, each newsletter was distributed nationally to scientists and PI's, technology developers, university faculty and graduate students, K–12 teachers, curriculum supervisors, and science writers. Organizations on the mailing list include NASA research centers and Teacher Resource Centers, as well as public and private associations, corporations, and laboratories. Other special groups on the mailing list included the presidents of Historically Black Colleges and Universities and Hispanic-Serving Colleges and Universities, directors of the National Space Grant Consortia, and university department heads in physics, chemistry, and engineering. The total distribution for each issue of the newsletter reached 9,000 by the end of 1996. This is a substantial increase from the two previous year's distribution (2,500 in 1995 and 934 in 1994).

From a national pool of 34 applicants, 8 graduate students were selected to receive support for ground-based microgravity science research during 1996–97 under the

Graduate Student Research Program (GSRP). Selections were based on a competitive evaluation of academic qualifications, proposed research plans, and the students' projected use of NASA and/or other research facilities. This brought to 43 the number of GSRP researchers actively working on microgravity projects in FY 1996. When added to the graduate students working with NASA-funded PI's, the number of graduate students directly employed in microgravity research now totals 823.

The Microgravity Science Research Program's World Wide Web (WWW) Home Page continues to provide regular updates on upcoming conferences, microgravity-related NRA's, enhanced links to the microgravity science research centers, educational links, and links to microgravity science photo/image archives. A list of important microgravity WWW Internet addresses is presented in table 11.

TABLE 11.—*Important microgravity WWW sites.*

NASA Home Page

Information and links to all NASA centers.
<http://www.nasa.gov/>

International Space Station

General and detailed information, as well as links to other sites such as Mir.
<http://issa-www.jsc.nasa.gov/index.shtml>

Microgravity and Space Flight

How microgravity is achieved and the importance of microgravity research.
<http://microgravity.msad.hq.nasa.gov/alntro/spaceflight.html>

MSAD

NASA HQ Microgravity Division and microgravity sites, and site with links to other news about programs and NASA Research Announcements.
<http://microgravity.msad.hq.nasa.gov/>

Microgravity News

On-line issues of Microgravity News, a newsletter about the field of microgravity science.
<http://mgnewww.larc.nasa.gov/>

LeRC

Links to microgravity fluid physics and combustion research.
<http://www.lerc.nasa.gov/>

MSFC

Links to microgravity science research in biotechnology and materials.
<http://www.msfc.nasa.gov/>

JPL

Links to microgravity low-temperature physics research.
<http://www.jpl.nasa.gov/lowtemp/>

Shuttle Flights

Information on all shuttle flights.
<http://www.osf.hq.nasa.gov/shuttle/>
or <http://shuttle.nasa.gov>

MSFC Microgravity Science Data Archive (MSDA)

Information on materials science microgravity experiments and other experiments.

<http://otis.msfc.nasa.gov/fame/Fame.html>

LeRC Microgravity Database

Information on fluids and Microgravity Database combustion experiments.

<http://www.lerc.nasa.gov/WWW/MCFEP/>

ESA Microgravity Database

Experiment descriptions and results, diagrams, and video sequences.

<http://www.esrin.esa.it/htdocs/mgdb/mgdbhome.html>

NASA Spacelink: A Resource for Educators

NASA Education information, services, and materials, including the Teacher Resource Centers.

<http://spacelink.msfc.nasa.gov/home.index.html>

Spacelink: Microgravity Teachers Guide 6–12

Microgravity Teacher's Guide with physical science activities for grades 6–12.

<http://spacelink.msfc.nasa.gov/Instructional.Materials/Curriculum.Materials/Sciences/Microgravity/Microgravity.Teachers.Guide.6-12/>

What is Microgravity?

The definition of microgravity and how it is obtained.

http://www.lerc.nasa.gov/Other_Groups/PAO/html.microgex.html

Zero-Gravity Research Facility

Description and images of the LeRC drop tower.

<http://zeta.lerc.nasa.gov/facility/zero.htm>

LeRC Microgravity Science Division Educational Information

LeRC microgravity educational activities and links to other NASA education sites.

<http://zeta.lerc.nasa.gov/new/school.htm>

Microgravity Investigator's Guide

NASA HQ Microgravity Division process for research selection.

<http://magpie.larc.nasa.gov/guide/guide1.html>

Microgravity Meetings List Bulletin Board

Bulletin board of meetings and symposia, and a list of societies of interest to the microgravity science community.

<http://zeta.lerc.nasa.gov/ugml/ugml.htm>

Microgravity Data Archiving

MSFC maintains the Microgravity Science Data Archive (MSDA), which houses video, photographic, digital and other data products generated during microgravity materials science and biotechnology experiments. Information concerning these experiments and their data products is contained in approximately 75 Experiment Data Management Plans (EDMP), which are available from the MSDA WWW site. In addition to the EDMP's, further information concerning microgravity experiments resides in the Microgravity Research Experiments (MICREX) database, which currently contains over 900 experiment records. The on-line MICREX database contains a link to ESA's

Microgravity Database. The MSFC photo archive contains approximately 4,300 photographs. An effort was begun in FY 1996 to digitize and make available through the WWW a subset of the MSFC photo archive. Over 350 VHS tapes and 16-mm films are cataloged in the MSFC video archive.

LeRC also has been actively building its archive collection in the areas of combustion science and fluid physics. Currently, there are over 536 combustion science papers and over 435 fluid physics papers in the archive; a listing of the papers by author is being made available on the WWW. In FY 1996, abstracts of the papers were being added to the LeRC WWW site. The experiments database

currently consists of information from a number of recent experiments, along with a few earlier missions. This information, contained in an EDMP database, includes such items as an experiment description; a list of publications associated with the experiment; a summary of experiment results and data; and a listing of videos, photos, and digital data. In FY 1996, archivists began gathering data on fluids and combustion experiments from missions prior to USML-1 (which was the initial task). Several of the EDMP's are available on the LeRC website. The paper abstracts and EDMP's will continue to be collected and put on the Website in FY 1997.

Program Resources for FY 1996

Funding for the FY 1996 Microgravity Science Research Program totaled \$159 million. This budget supported a variety of activities, including an extensive microgravity research program; development and flight of microgravity shuttle missions; *ISS* planning, technology, and hardware development; educational outreach; and *ISS* facility-class hardware development. The funding distribution for combined flight and ground efforts in the various microgravity research disciplines is illustrated in figure 1.

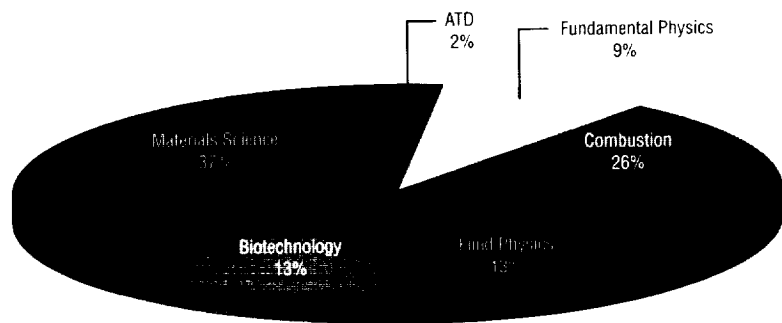


FIGURE 1.— FY 1996 microgravity funding distribution by science discipline: \$159M.

Figure 2 presents the funding distribution by microgravity mission. Included in this representation is the Research and Analysis element that supports the ground-based microgravity principal investigators not covered in a mission-specific budget. The Multi-mission category includes costs not identified with a specific mission, such as administration, the ATD Program, science support activities, data management and archiving, National Institutes of Health cooperative activities, and infrastructure. The Small Missions element is the portion of the Microgravity Science Research Program using the space shuttle small payload systems (e.g., Get Away Special Canister Program), shuttle middeck experiments, and sounding rockets. The *Mir* element represents funding for experiments that are planned for the *ISS* and *Mir* programs. Included in this category are the Fluids and Combustion Facility, the Biotechnology Facility, and the Space Station Furnace Facility.

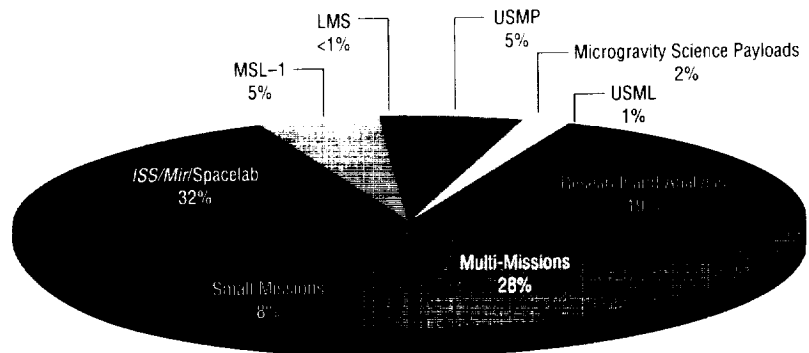


FIGURE 2.— FY 1996 microgravity funding distribution by mission series: \$159M.

The Microgravity Science Research Program operates through five NASA Field Centers. Figure 3 illustrates the funding distribution among these Centers (and includes NASA HQ funding). The Microgravity Science Research Program science discipline emphasis is as follows:

- MSFC—Materials science, the fundamentals of biotechnology, and the PCG portion of the biotechnology discipline.
- LeRC—Combustion science, fluid physics, and microgravity measurement and analysis.
- JSC—Cell and tissue culture portion of the biotechnology discipline.
- JPL—Fundamental physics.

Technology development tasks were also funded in FY 1996 at each of the NASA Field Centers.

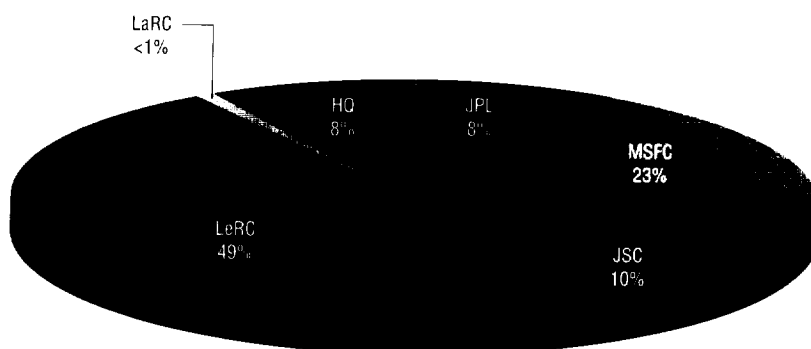


FIGURE 3.—FY 1996 microgravity funding distribution by NASA Field Centers: \$159M.

For More Information

NASA's goal is to improve the quality of life on Earth by utilizing ground- and space-based research to promote new scientific and technological discoveries. The Microgravity Science Research Program plays a vital role in our Nation's economic and general health by carefully selecting, funding, and supporting scientists across the country. It also serves as an important link in the international endeavors that are the hallmark of America's space program, which is doing business better, cheaper, and faster through cooperative ventures and other new ways of doing business.

By disseminating knowledge and transferring technology among private industries, universities, and other Government agencies, NASA's Microgravity Science Research Program continues building on a foundation of professional success, evident in the number of publications and conferences attended, while reaching out to encompass the populace at large. Educational outreach and technology transfer are among the Program's top goals, making the benefits of NASA's research available to the American public.

Space shuttle and *Mir* research missions, as well as experiments performed in short-duration microgravity facilities, are yielding new understanding about our world and the universe around us, while paving the way for long-duration microgravity science on the *International Space Station*.

For more information about NASA's Microgravity Science Research Program, contact:

Microgravity Research Division
NASA Headquarters
300 E Street, SW
Washington, DC 20546-0001

Fax: (202) 358-3091
Phone: (202) 358-1490

WWW address:
<http://microgravity.msad.hq.nasa.gov/>



National Aeronautics and
Space Administration

NASA TM-108536